Micro-scale dynamics of house consolidation process in Lima

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Contents

Abstract

House consolidation is the inherent component of informal urbanization process in Lima; control of house consolidation is a central criteria employed by municipal managers to implement two main activities for the improvement of housing conditions: legal recognition and infrastructure construction. This study investigates the use of agent-based models as a new and adequate research method for replicate consolidation process dynamically, and for predicting house transition data. Simulating informal urban development over time is useful for municipal managers in their activities of regularizing houses that emerge in small settlements (parcels) across Chillon valley. Modeling house consolidation process is a great challenge as it addresses two independent but interrelated dimensions of state configuration and social interaction. Cellular automata and agent-based models of consolidation applies growing algorithms to generate hypothetical but accurate views of urban space at block level.

Informal development has specific and unique characteristics compared to formal real estate development. These social-based characteristics such as progressive self-help construction and social interaction within a small community of neighbors, allow to devise rules of state transition based on observed empirical patterns and social theories of social influence and contagion. Moreover, two particular features of informal development make model design and implementation straightforward: consolidation is a progression across states of new urban components; and individual houses are being constructed independently, thus decision to develop is up to household given its housing needs, financial affordance and social interactions with fellow settlers.

In this research focus is in the specific case of an agricultural valley located in the urban fringe, where former agricultural parcels are being sub-divided independently as well, to make room a regular layout of blocks and houses. Modeling and simulation of these new urban spaces is made at the bottom level where consolidation is better identified and described; at this scale simulation refers to replicate long term state transition as a result of individual decision making and social interactions. This urban simulation at micro-scale generates large amount of fine-grain data that is likely to be useful by municipal managers who are implementing activities of illegal land regularization, which consists mainly in formalizing property deeds and improving urban infrastructure.

1 Introduction

Informal urbanization is causing uncontrollable growth in Chillon valley, located in the northern boundary of Lima metropolitan area; this phenomena operates at parcel scale, where small tracts of land are being subdivided independently; in these former agricultural parcels, individual housing units begin to be self-built through a long period in a process called consolidation. No urban services are installed prior house construction. According to Housing Census Bureau (INEI 2009), actual deficit of houses in Peruvian market has been estimated to be around 1,8 million units. Formal market supply is not completely providing affordable house access to people, therefore one of the options followed by poor households is to draw upon informal developed land, where lots are being sold and independent houses are being built out of the regulation framework. In 2012, around 50 000 houses, out of a total of 120 000 units, were built without legal permission from municipalities, it represents 40% of annual housing stock; in the same year, around 80 000 houses were self-built, for instance the value of self-help building activity was estimated to represent 3.6% of Peruvian GDP (Arellano Marketing 2012). Thus, an important feature of informal housing development is independent pursue expressed through self-help construction, moreover it is providing an alternative way of building the city in parallel to formal regulations. In rapid informally developed areas located in the northern fringe of Lima metropolitan area, municipal managers need of accurate and customized information on future conditions that could help them to track improvement in specific sectors and to propose tailored measures for each block, given the common trend where small spaces are being urbanized uncoordinatedly without central control. Informational tools at micro-scale could allow them to address individually each block and parcel, and therefore project future growth, consolidation, and densification in a customized way and towards a micro scale incorporation within the formal areas in the city boundary, which are changing rapidly as well. New spaces that arise continuously in informal expansion areas of cities are not linked to older consolidated areas, mainly because of its lack of infrastructure and basic services. These transformed artificial and natural spaces emergent as a new urban system require to be incorporated into the city system operation, making it part of its multiple functions and therefore economically valuable to sustain the gradually appearing new urban compounds. New needs, opportunities, fashions, technologies and ideas that arouse bottom-up are challenging top-down plans (Alfasi et al. 2012). Urbanization in general and informal urbanization in particular have been studied through modeling; an evaluation made on state-of-art models of slum dynamics (Roy et al. 2014), found that these models use macro aggregated data and are not spatially explicit. As a result these models neither replicate the process at its actual scale nor provide causal mechanism that generate emergence of spatial patterns from bottom-up.

Central idea of this research is the emergence of spatial patterns from social interactions in the context of informal urbanization at block scale. "Conditions of increasing complexity can evolve into clear structures and relationships at a higher level, where other structure-defining values and norms exists" (Zuidema and De Roo 2004). Proposed solution and main contributions of the dissertation are related to the concepts of: bottom-up spatial processes, social interactions, space and time patterns of consolidation, dynamics of house state and its transition; "cities in particular and urban development in general, emerge from the bottom up and spatial order we can see in patterns at more aggregated scales can be explained only in this way" (Batty 2005).

Visual identification of individual households in high-resolution satellite imagery allows to describe the physical state of housing units and relate it to socio-economic variables; also actual data at micro-scale can be used to validate computational models. The role of interacting neighbors constituted as social network within housing block space and its influence on upgrade decision-making, is hypothesized and used to replicate the relevant dynamics observed in real case of house consolidation in the urban fringe of Lima metropolitan area. To evaluate hypothesis on influence, we consider two simple structures of spatial adjacency and social network respectively at the scale of the block; at this level, social interactions between households are determined by household socio-economic status, which in turn are based on house construction state. Thus, as a result of influence upgrade decision spreads across space and social network.

This bottom-up approach is implemented using both cellular automata and agent-based models; these models are different from other slum dynamics models because it acknowledges explicitly space, it uses individual level data, and finally, it validates outcomes (spatial configuration) using data set acquired from real world. In a weak regulative context, where only physical layout of boundaries of parcels and blocks appear permanent during informal urbanization, the study of changing interactions along time between different classes of stakeholders and its relation to a vast array of construction states at block scale, could determine changing spatial characteristics of emergent urban system. This bottom-up quantitative approach mach consolidation system operation scale better than usual top-down direction used in either modeling or planning.

1.1 Objectives

There is evidence to indicate that individual housing needs and group influence drives consolidation process across time and space. Along with social dimension, spatial distribution of individual attributes also affects trajectories of state transition. Its spatial and social outcomes can influence municipal decision at block scale. This study is focused on the physical aspect of state transition that emerges from social interactions. State of houses and urban density at block scale are indicators that are used by municipal managers to improve housing conditions via ownership legal entitlement and infrastructure construction. Identifying and projecting data on consolidation remains a challenge for municipal managers who need updated data to implement more precisely their activities. Traditionally district scale aggregated data have been used to estimate micro-scale conditions.

Modeling have been seen as an appropriate method to address large and heterogeneous systems such those existing in rapid growing urban areas. Handling research on these areas via field surveys is a common procedure; however, results from experimenting upon the real thing may become obsolete in terms of time as system change every moment. New computational tools are now available to study and model complex socio-spatial systems, oriented to generate data from simulation. Agent-based modeling (ABM) has attracted attention as a viable method to reproduce micro-scale replication of dynamic urban growth processes. Research on computational simulation of urban processes have found that they are accurate, resource efficient, and provide low cost solutions for generate data useful for planning and policy making. House and block scale consolidation have significant urban management implications, but there does not appear to be any published literature on micro-scale modeling and simulation of house state transition, considering state as an inherent and changing attribute of house within informal development areas. Many models even those at micro-scale simulate urban growth as land use change or footprint allocation of urban structures including houses.

"Despite today's common wisdom that urban system are complex, we know relatively little about how they evolve from micro-scale processes" (Irwin et al. 2009). Given the absence of a theory to explain observed phenomena of house consolidation, main objective is to employ quantitative analyses to build models and perform simulations that better represent consolidation system and the spatial and temporal patterns of state transition; furthermore, this approach address a requirement to inform planning, considering that data on future house conditions is inaccessible, which in turn provides the reason to choose a modeling methodology. Therefore, two specific objectives of this research are:

- Replicate consolidation process,
- Predict house transition data.

In both cases methodology is inductive and exploratory, using scope and theoretical framework of the Computational Social Sciences.

1.2 Contributions

Main contributions of research are:

- Provide a modeling approach to investigate and replicate the process at micro-scale, which allows the simulation of dynamic changing conditions of state in houses, and subsequent emergence of spatial and temporal patterns of consolidation at block scale. It enables to predict future conditions useful to better manage ongoing densification and concurrent provision of utilities in informally urbanized areas. As Inostroza (2017) suggests "when informal urban development challenges standard urban planning, monitoring arises as an important aspect of urban governance".
- Acknowledge the role of interacting neighbors (constituted as social network within housing block space) and its influence on upgrade decision-making, and operationalize it as a computational model; social interactions are hypothesized and used to replicate the relevant dynamics of state transition at bottom level and the emergence of spatial and temporal patterns, similar to those observed in real case

of house consolidation in the urban fringe of Lima metropolitan area. In performing this behavior, it is assumed that households perceive and monitor constantly the state of their block neighbors.

- Specify a theoretically sound model with empirical foundations that convey complexity (networks) and social (diffusion) theories together, devising a analogy of consolidation at micro-scale, representing dynamically how households perceive the neighborhood and take decisions on upgrading house state. Transition rules are devised as algorithms from the conceptualization of consolidation system as an influence-driven and stochastic state transition process.

- Devise a data acquisition method at individual scale of houses, using visual identification of high resolution satellite imagery; data is available only in visual spectral range as it is provided by freely available Google Earth source.

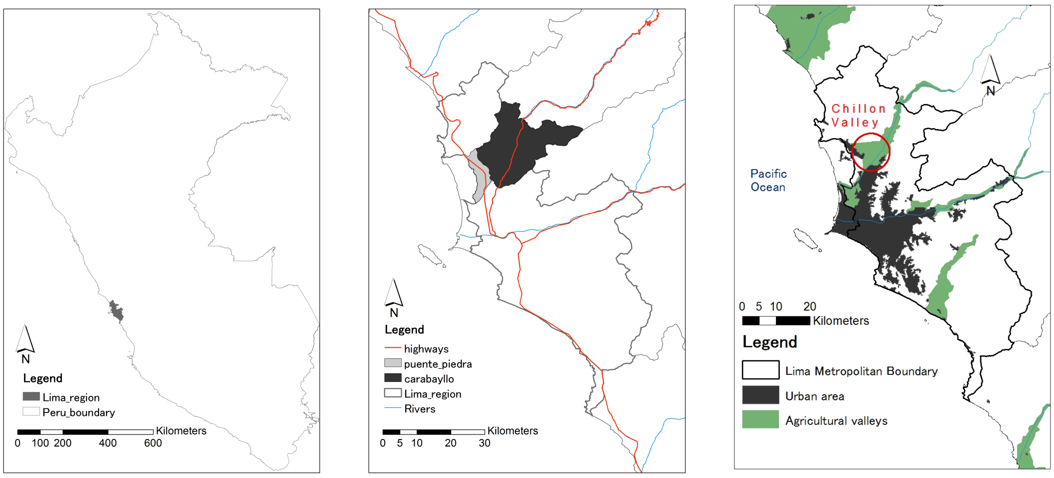
Systematic understanding of consolidation system may be employed in management and provision of financial and utility services in this dynamic system, aimed at improving the built environment and shortening the long lasting process of house and urban consolidation in informally developed lands. In the proposed approach of consolidation at micro-scale that is operationalized in this study, these are respectively the object and scale of analysis. These emergent structures at block level match the dimension or scale where actual policies and budget allocation are implemented in formalization efforts and public utilities construction at local level of municipalities. Characterizing this process and the resulting physical and demographic structure, make it possible to municipal managers to handle urban growth and plan the provision of infrastructure in informally developed parcels.

2 Background

In this chapter a wider scope on Peruvian case of informal development and house consolidation is presented, it includes evolution along the last 60 years of public housing policy addressing the increasing housing demand and access by poor city dwellers. It identifies and describes main features of consolidation process in informally developed areas under the current policy framework. The object of analysis is the consolidation process, which is being driven by interactions among individuals. A broad socio-spatial context is provided by informal urbanization focused in the case of Chillon valley, which is located in the northern urban-rural fringe of Lima metropolitan area (Figure 1). Consolidation is a phenomenon of progressive improvement of physical house conditions, through self-help construction and within a context of illegal occupation of already subdivided parcels, where houses are self-builded independently by each household. Normative planning framework at municipal scale is not addressing heterogeneity in housing structure and functions at parcel scale in the context of informal development, neither it addresses continuous densification at bottom level. Static control of informal urbanization is conducted by assumptions that consider urban areas as homogeneous spaces occupied by aggregated housing following centrally controlled regulations. That control fails to regulate both urbanization and house consolidation processes, as it can be seen in multiple ad-hoc regulations that regularize consumed realities. Moreover, theories of urbanization provides understanding at macro-scale of urban growth with little insight on influences derived from individual interactions and the spatial dynamics it generates.

2.1 Relevance

Proportion of urban population in Peru has grown from 68.7% in 1990 to 78.7 % in 2015, and it is estimated to reach 82.0% of total population in 2025 (INEI 2009). The most common type of dwelling in Peru is the single-family detached house, they comprises 76.5% of total individual housing units, while the proportion of apartments is 17.4%; regarding ownership, 69.3% of the total individual housing units are in individual property and 14.3% are rented; out of those that have owner a 51.2% have title deeds (INEI 2014). According to Housing Census (INEI 2009), actual deficit of houses in Peruvian market has been estimated to be around 1,8 million units. Formal market supply is not completely providing affordable house access to people, therefore one of the ways is to draw upon informal developed land, where independent houses are being built out of the regulation framework. Around 50 000 houses, out of a total of 120 000 units, were built without legal permission from municipalities, it represents 60% of annual housing stock (Arellano Marketing 2012; Ministerio de Vivienda 2013). An important feature of informal housing development is self-help construction. Mentioned study by Arellano Marketing (2012) states that 80 000 houses were self-built in that single year; for instance the value of self-help building activity was estimated to represent 3.6% of Peruvian GDP in that year.



(a) Peru and Lima Metropolitan area (b) Carabayllo and Puente Piedra municipalities (c) Chillon valley within Lima Metropolitan area

Figure 1: Location of study area

2.2 History

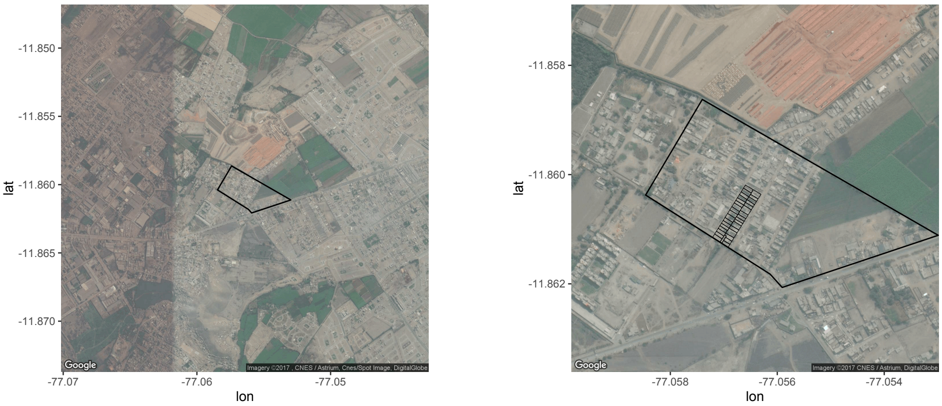
Sixty years ago, during the late fifties, economic liberalist and then Prime Minister Pedro Beltran established a core policy principle to address increasing housing demand: "house that grows" (Collier 1975). Under this policy umbrella, intended for low income households, supply is provided through promoting the development of either informally or formally constituted basic houses units, which are laid out in available land, and then expected to be progressively built according to household needs and affordance. Around the same time, Turner (1963), who worked several years in Lima housing activities, advocated this schema of house provision highlighting features like self-help and autonomy, although he disliked government intervention. Since then, self-help construction has been accepted de facto continuously across different governments and ideological trends (Bromley 2003), and even has received government support in either organizational or financial provisions. In the seventies, Government reformed the building regulations, allowing for the first time to make progressive development with much simpler requirements than the traditional procedure; therefore, prospect households organized in housing construction associations and cooperatives could act legally without arousing suspicion concerning the illegality of agricultural land acquisition and use change (De Soto 1989). This long lasting national housing policy recognizes self-help house building as a valid mechanism for house supply that involves individual effort by progressive self-help construction, which is driven in response to independent and changing housing needs (Williams 2005). This scheme requires gradual capital investment by individual households, along with public support by providing cheap land, basic utilities or other individual or grouped subventions. In the case of informally developed houses, since the nineties this policy has been implemented along with granting of property titles to householders, following De Soto (1989) recommendations to foster legal ownership in order to provide urban poor people access to credit. In this regard, public support and subvention to self-help construction was stablished through banking system since late nineties. Thus, current role of public institutions (at national, metropolitan and local level) is recognized as promoting and easing formal house access conditions through private investment, in order to match requirements from low income population. In the case of housing formal development, public budget is allocated to individual households via subvention through banking system, oriented to buy developed land or to hire constructors towards procuring houses whose structure admits progressive growth. It should be remarked that financial access and support only applies to formal or formalized houses that can show property deeds.

2.3 Empirical observation

Visual identification of house states using high resolution satellite imagery has confirmed above-mentioned long term process of consolidation at house scale in Chillon valley. Progressive lot occupation and house construction occurs without previous setting of urban facilities (water, electricity or paved streets), thus a precarious unit comes first starting the process of house consolidation. Spatial allocation of these informal houses is random at block scale reflecting individual households self-building houses independently. This explicit observation of the houses grouped into blocks provide parameters and conditions for further spatial characterization and modeling of the process.

Individual and independent pursue is an important characteristic of self-help building. Progressive house consolidation responds mainly to changing housing needs within the household; other particular conditions such as holding a property title do not drives decisively decision to upgrade (Williams 2005). This personalized character of consolidation process leads to an idea of individual trajectories of state transition; this trajectories when aggregated within the space and scale of the block, makes a dynamic and heterogeneous urban structure to emerge at upper urban scale. As individuals gather within clearly and regular established space of the block, proximity is credited to exert influence in householders decision to upgrade. It should be noted that spatial layout of subdivided land has regular form, where both blocks and lots resembles high density formal development counterparts. Former agricultural valleys in Peruvian coast are being subdivided and developed informally; this study focuses in the process of informal urbanization located in Chillon valley, which is located in the northern fringe of Lima metropolitan area; in this newly expanded area of the city, house consolidation process is changing progressively the urban structure. Calderon (2015), cites a particular characteristic of informal urban development in Peruvian cities; his study found that across available land around expanding cities, land owners are small agricultural owners who follow independent and speculative behavior. Therefore, at the urban fringe parcels develop independently and create a fragmented landscape at meso-scale (Figure 2).

Growth is restricted by spatial boundaries of subdivided agricultural parcels where subdivision create blocks space, which in turn leads to house infill within the regular



(a) Informally developed parcel

(b) Block scale development

Figure 2: Subdivision and consolidation within a former agricultural parcel in Chillon valley (Source: Cadastral Map 2008, Google Earth 2017)

layout of these residential blocks; finally, newly created urban space generates both physical and demographical densification. Infill and densification properties constructs a neighborhood where social structure emerges due to proximity, providing the substrate where perception of physical states and social influence are assumed to drive consolidation process (Figure 2). This socio-spatial evolutive process of consolidation, performed by highly independent and decentralized households, generates outputs at upper scale of block that are difficult to represent and predict, since its changing dynamics are not linear. In the specific case of Chillon valley, where the bulk of agricultural land (90%) comprises parcels of less than 5 ha. (Figure 3), former agricultural parcels are subdivided and sold to precarious proprietors; in this type of informal development lots are cheap to buy and match demand from urban poor, because subdivided land do not compliment urban regulations. These informal residential sectors are densifying through house consolidation and are being formalized by authorities who implicitly recognizes the validity of this type of urban growth and the failure of top-down local and metropolitan planning regulations. In the case of the valley, top-down planning is neither reflecting nor addressing the large amount of urbanization activities at parcel scale, which are being implemented by informal means. State transition is a key indicator to understand and manage this process of urban growth. Bottom-up development implies individual decisions at house level that make the urban fabric to consolidate from the aggregation of structures that upgrade independently. At bottom level houses organize within regular space of the block, which is the fundamental frame that articulates urban structure and functions at this scale. Functioning of house consolidation reflects the social character of this process (Barros 2012); state composition and configuration are changing within the space of the block, which constitutes the basic component of urban fabric. Neighbors can plausibly interact within physical space of the block due to proximity, which results in self-organized state transition trajectories; both interactions and change of state are

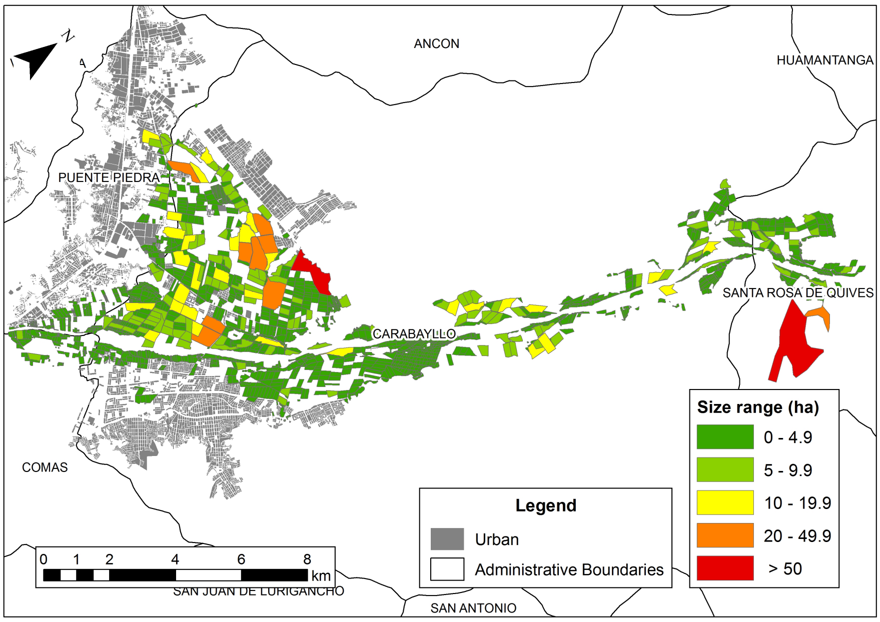


Figure 3: Size ranges of agricultural parcels in Chillon valley (Source: Cadastral Map 2008)

credited to be the elements behind the dynamics. Municipal planning and management are required to address this dynamic of growth, making an adequate use of public and private resources by anticipating future state conditions at block scale, which provides spatially focused demographic quantification and spatial location of related needs for utilities and equipment that can finally improve and enhance social and economic functions within new urban space. This is in fact what organized settlers associations in Peru have been doing, recognizing their small scale infrastructure needs, bargaining it with local authorities and implementing through tailored development programs at bottom scale. However, a clear recognition of this fact as part of the planning process within a conceptual framework could improve management in areas with similar characteristics of land sub-division and informal consolidation; these processes are in fact occurring across Peruvian coastal valleys where small towns are growing informally towards agricultural areas.

Consolidation within the block creates dynamic urban pattern at upper level. Characterizing this process and the resulting physical and demographic structure, make it possible to municipal managers to handle urban growth and plan the provision of infrastructure in informally developed parcels. Bottom-up consolidation process acknowledges grassroots organization to access infrastructure in informally developed settlements, and thus serve as a proxy to recognize specific (physical and demographic) conditions while addressing this actual dynamic condition where self-organized households along with local authority have an important role in planning and implementing infrastructure provision. Densification and infill concepts derived from particular consolidation dynamics of

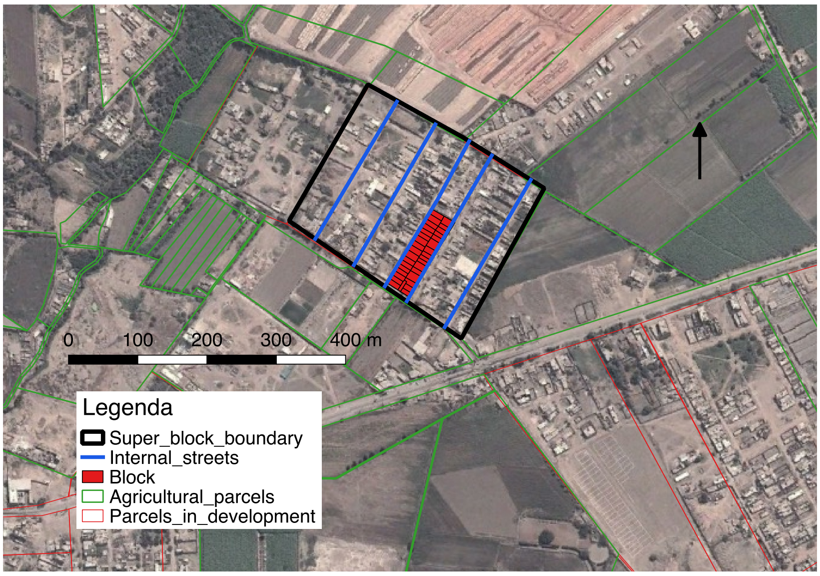


Figure 4: Informal super-block features in Chillon valley (Image: Google Earth 2013)

house state transition in informally developed parcels, can be used to generate household-based future scenarios oriented to plan and satisfy infrastructure needs. Therefore, scale proceeds from addressing individual housing requirements towards supply of communal equipment to blocks in development within former parcel, now constituted as an urban super-block (Figure 4).

Informally developed super-blocks are composed by a small number of blocks that belong the same former agricultural parcel maintaining across time important features such as access and perimetric roads. At this upper level, evaluation of aggregated housing conditions provide useful information to decide the scope of infrastructure works and to quantify resources required including preliminary financial provision schemes. It is important to remark and recognize that the block is the basic component of the informally developed parcel; moreover, the fact that former agricultural parcel generally has small surface (5 ha.) and keeps its boundaries after development, generates urban spaces that resembles the configuration of super-blocks, which are surrounded by access roads used by former agricultural parcels and articulated internally by new narrow streets that structure block configuration.This spatial shape of urban development allows to manage specific needs from designated parcel-based units where housing units share common ground, location and road access.

During legal formalization process, implemented by municipal authorities, both construction and development rules are relaxed, in order to recognize the effort of former illegal settlers and the fact that strict regulations do not ease house acquisition for urban poor. By regularizing informal conditions, the first step taken is to provide individual property deeds along with parcel-scale formal acknowledgement of parcel development that allow former informal settlements to be annexed within formal urban space, where they share both benefits and duties of formal housing units; thus, after regularization newly formalized houses and settlements are subject to taxes or eligible for installation of basic infrastructure.

2.4 Approximation to the problem

Problem is derived from empirical observations through successive approximations using research questions that considers consolidation process as the object of analysis.

1. How do houses state change heterogeneously over the selected 14 years period of self-building process in the context of informal urbanization? observed individual state differentiation between houses requires a descriptive and explanatory narrative on the process and its spatial and temporal significance. Factors that made construction state transition possible and drive state transition operate at house scale, and can be identified and retrieved using both physical and social attributes from either primary or secondary sources.

2. What mechanism keep individual state differentiation between houses across the period? observed spatial heterogeneous pattern of house construction states appear into the space of the block along the mentioned period; mapping of states at individual house scale shows actual diverse and heterogeneous pattern would emerge from independent social behavior (decision-making) along the studied period.

3. To what extend individualizing states along time is effective at characterizing consolidation process? It acknowledges the existence of different construction states and the importance to include these stages within the conceptual framework, explanation and planning outcomes.

4. Could the particular differentiation between houses suggest tension and the occurrence of interactions between households due to spatial proximity in the block? This questions suggest implicitly the existence of social interactions and the necessity to include it within the analysis. Literature suggest that spatial proximity within the block can generate effective links between neighbors in the block along time. Social organization is also a requirement that local authorities ask in order to provide support to these communities. Although consolidation is a dynamic process of house state transition driven by individual decision-making, in the small space of neighborhood it is plausible that households interact and therefore influence is likely expected. Thus, it can be assumed that as a consequence of influence from a household of greater status, a neighbor household may decide to upgrade its house state according to both individual housing needs and economic affordance present at a given time within the block.

5. How does social influence is driving spatial and temporal state transition? taking into account the construction state on a neighbor house, which in turn belongs to

a group of individual and independent houses, social dimension that appears in the space of the block should be handled by using social theories of influence. To implement this rationale, empirical data and system conceptualization via computational models can be used to isolate the elements that plausible causes consolidation. Acknowledging the block as the space where individuals interact, provides the advantage of clearly delimited boundaries and group membership by fixed number of house units across time.

Finally, to make it possible to answer above mentioned questions it can be asked:

- How effective is an individual-based approach to describe and explain consolidation?

- How to combine, operationalize and measure social interactions and spatial processes?

These last two questions synthesize the scope of this investigation, and provides the logic to further develop and implement research method.

2.5 Defining a research problem

The object of study and phenomenon to be researched is house consolidation; it is a system composed by fixed block space and changing states of houses. Observed consolidation process in Chillon valley generates heterogeneous spatial outcomes derived from independent actors with diverse housing needs, who are acting without central control; therefore, it can be inferred that individual household behavior is driving consolidation.

2.5.1 Household behavior driving consolidation

Consolidation process generates continuous change in the physical structure of individual houses, frequent measurements of these attributes are not possible due to high costs that is required to perform field work or remote sensing continuously. Construction state is a dynamic and non-linear variable; therefore, monitoring the change and elucidating the mechanism of change in the structure, provide this investigation the elements to better describe house consolidation process at block scale. Moreover, the aim is to represent a model of the system at block scale that makes it observable using only state and location attributes.

At this micro-scale, occurrence of interactions between neighbors is plausible; Ioannides (2010) argues that “in the context of housing and other decisions, close physical and ’mental’ proximity is likely to be associated with individuals’ caring about the actual or expected behavior of their neighbors”. At block level consolidation causes house infill and densification that is noticed through the spreading of urban fabric. These emergent structures at upper level match the dimension or scale where actual policies and budget allocation are implemented at local level of municipalities. Informal development has been largely ignored in plans and regulations issued by public institutions; they have

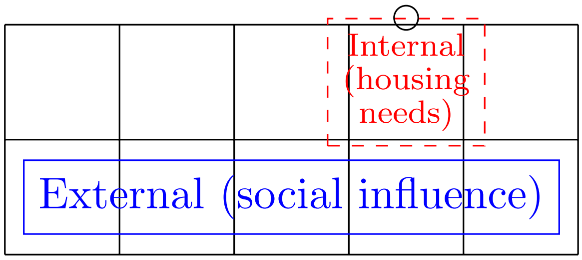


Figure 5: Internal and external spaces of consolidation within a block

been responding reactively acknowledging current conditions and regularizing them on specific-case basis; this institutional behavior has become a common practice at national, metropolitan and local level in order to include large amount of houses into the formal space of the cities. Using the above mentioned analogy of house consolidation caused by social interactions, and implemented as a computational instrument, it is possible to represent and describe dynamic trajectories towards consolidation that results in diverse state compositions and configurations along time.

2.5.2 Matching individual scale to urban planning

Urbanization in general and informal urbanization in particular have been studied through modeling, but in general these models use or generate aggregated data in large scales (Roy et al. 2014), however, these models are applied to recreate and explore urban growth in different scales in order to describe the problem and in some cases provide practical insights and solutions on spatial trajectories of growth or development. However, as Crawford (2016) indicates, modeling dynamic urban realities is not an easy task, because "formal analytic models of complex systems are not tractable because of a combination of adaptive behavior, non-linearities, the difficulties in fully specifying initial conditions and emergence". This investigation recognize that complex and computational approach to study informal urban growth in northern Lima border can provide useful theoretical insights to understand function in largely dynamic consolidation system; according to Batty (2005) the study of non-planned development allows understanding of city natural evolution at bottom level, and recognizing the complex and dynamic nature of the city as seen either at individual or city scale. Moreover, in informal development, "many of the characteristics we associate with informality are, in fact, natural by-products of the fact that the informal owner is fundamentally a micro-entrepreneur, the owner of a small firm" (Maloney 2004). As the very nature of informal urbanization relies on the individual pursue of households who choose to occupy the land and self-build its houses following an independent decision based on internal housing needs and external influences due to interaction (Figure 5). A method that acknowledges this expressed characteristic is best suited to replicate the process and explore how it functions. Therefore, simulation of the spatial and temporal process of consolidation at block scale, allows to understand the dynamics at bottom scale and predict growth.

Urbanization is the process of increasingly agglomeration of people in nuclear settlements or cities and in many cases occupying former farmland space; this process has many implications on function of both environment and society; from a geographical perspective, the process of agglomeration is spatially dynamic and demand resources from the urban region and beyond in order to keep its complex functions (Forman 2008). Urbanization is essentially an explicit aspect of the relation between human and environment that creates both benefits and problems; regarding the provision of nature services on cities, Forman (2008) argues a requirement for a new strategic approach that join together people and nature in a whole combined system. On a professional approach Milburn et al. (2003) argue that "there is an increasing demand for research in Landscape Architecture to inform design decision-making". Focus at bottom level of objects in the system allow the researcher to investigate the primary causes that are going to cause emergence of new objects in the upper spatial levels. At this point it is important to mention one important methodological problem that arises from observing, and analyzing change along the time; the problem is that "the patterns obtained from remote sensing data usually represent the complex aggregated outcomes of many different individual processes, making it difficult to disentangle the effects of different variables and trends of interest" (Herold, Couclelis and Clarke 2005). In addition (Lee 2001) observes that "in an urbanized environment, the geographic pattern of residential development is a complex phenomenon to model quantitatively".

It is time now to mention the scope that provides the specific social and spatial context for the current investigation; recent article by Barros (2012) acknowledges the usefulness of complexity approach, mainly because the inherent features of independent and decentralized growth and resultant spatial heterogeneity that characteristics informal development. She noted that the bulk of the housing stocks in Latin American cities now consists of upgraded (or in the process of upgrading) low-income residential areas, with a large number of spontaneous settlements. "Accepting the logics of settlement formation, from house to the city, and understanding the urban pattern it generates by aggregating small spaces, allow us to act in different way when addressing informal settlements issues" (Saez et al. 2010).

2.6 Solution proposal

An empirical study at the very bottom level of informal urban growth is suggested in order to address the dynamic, decentralized and non-linear process of house consolidation. Research is oriented to explore and test an argument that supports the model via merging of spatial and social concepts that permits to build an analogy of the interactions between individuals and emergent spaces within the boundaries of a housing block (Figure 6); this analogy acknowledges the fact that individual-based processes of physical, spatial and social change such as consolidation are difficult to track and interpret. The study of a fixed period of consolidation is an strategy that allows to identify, describe and model consolidation, oriented to investigate future implications of this process. "Open evolution may hamper the quality of predictions that can be made about the future, but geographical knowledge of past dynamics may help to make forecasts more

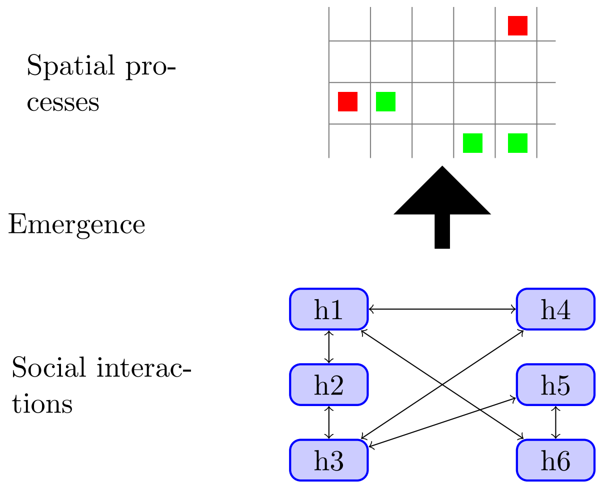
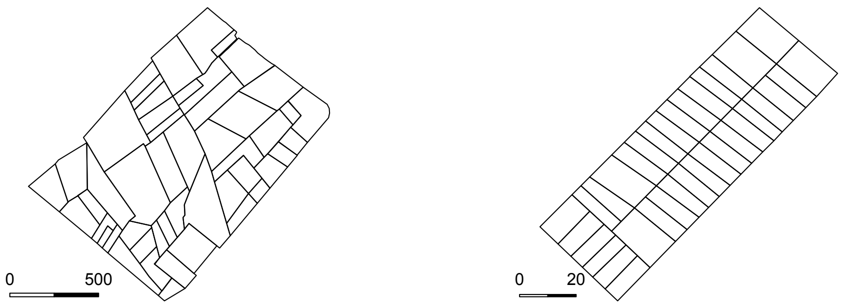


Figure 6: Proposed mechanism of house consolidation (based on Portugali 2016)

certain" (Pumain 2017). Emergent spatial patterns from interactions is an idea inspired by Batty (2005) and Portugali (2016), who argues that the city as a complex artificial system emerges out of the interactional activities of its agents at bottom level (Figure 6). To perform this investigation, an individual based modeling technique is best suited to replicate particular settings and conditions of house consolidation observed in Chillon valley, because it considers individual interactions and the "use of spatial networks to explore the geography of emergent and collective behaviors" (Alizadeh et al. 2016).

Taking into account that the briefly described phenomenon of consolidation within an informal development setting is very complex to study, it is understandable to focus on essential qualities of behavior (Shannon 1975); therefore, selected spatial scale permits to identify construction state in each individual house, providing a valuable data-base at individual level. Cultural and natural problems derived from urbanization can be studied within a broad spectrum composed of several approaches and addressing issues that could range from housing to ecosystem services. As a complementary approach, focusing informal urbanization from policy and planning perspectives provides an implicit organizational premise: urbanization uses available cultural and natural resources towards densification, which is the observed course of action in the case of informal development and house consolidation. Organization implies a conceptual framework where cities or urban areas are viewed as subjects of management in certain degree and according to very specific and perhaps short-term demands from stakeholders; in Chillon valley observed spatial hierarchy from bottom-up is composed by houses-blocks-parcels scheme (Figure 7).

From an organizational approach, the urban system is described as a population of actors and its environment where they perform determined relations. It is proposed that actors can behave following certain rules, which range from simple deterministic to heuristic that allows them to act autonomously. Actors are influenced in its decisions by social attitudes and preferences, and by public normative and bureaucratic rules (Jack-



(a) Parcels (b) Block and lots

Figure 7: Spatial hierarchy of spatial units in Chillon valley

son 1980). Empirical observation suggest that this behavioral pattern exists in Peruvian conditions; moreover, legal framework and public institutions are focused more in control great scale investment, and less oriented to regulate small owner and land-based production. “Organization of space also undergoes change, because the values change in the course of time” (Jackson 1980); this quotation brings the discussion back to informal urbanization and its nature that allows progressive self-help construction; it appears to be scientifically relevant to know how actors belonging the organized spaces and less organized institutions, have been behaving in order to search for some spatially related pattern, which can inform or explain the dynamic trajectory of landscape change (cultural, natural and perceptual) from the change in land use. In looking for its individual objectives it is assumed that actors seek a criterion function of acquisitive objectives, which according to Shannon (1975) means acquiring resources or attaining states, rather than keeping or preserving them. Thus, changing discrete states of the urban system in specific dates, can be related to a framework of rules given to actors in order to behave in a way resulting in observed outputs. Saez et al. (2010) argue that accepting the logics of settlements formation, from the house to the city, and understanding the type of urbanism it generates, as aggregation of small spaces, allows us to act otherwise in the informal settlements by focusing on the small scale of housing and its intermediate spaces as a motor of development; they further advocate to incorporate or formalize the urban uses that are given to this bottom scale incorporating to the formal upper structure of the city. As Alfasi et al. (2012) suggests “planning is a dynamic process”; these authors advocates to address the bunch of urban issues that are emerging bottom-up, which are challenging top-down plans; these challenges are reflected by “the abundance of plan revisions” and require dynamic solutions that acknowledge role of individuals. The ultimate goal to improve housing conditions both in quality and quantity, taking into account the dominant market economic context present in Peru and the individual role of households in self-building their houses, is to devise a schema of planning that recognize continuous change in social and spatial conditions. Results of the study are expected to monitor spatial effects of consolidation due to current individual and private housing development performance.

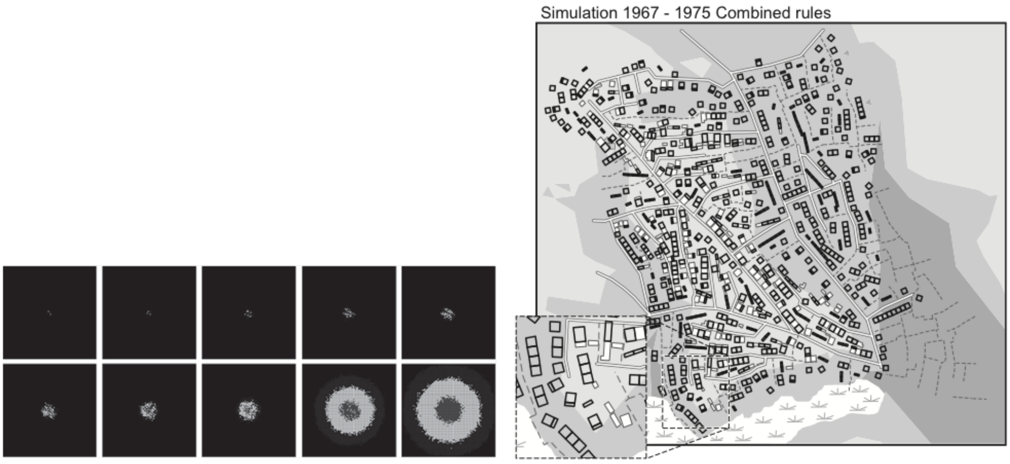
2.7 Methodological problem

Micro-scale investigation can be summarized as obtaining data at individual scale, useful to model and analyze consolidation system in spatial and social dimensions, and discover patterns that provide insights on the mechanism driving consolidation. Individual data at bottom level, is first required to derive a simple process of consolidation that comprises building model structure and devise the algorithm that drives simulated interaction between categorized householders; finally, individual based models are employed to scale up interactions between individuals in order to recreate dynamics of emerging spatial and temporal outcomes along time. This research investigate urban system at micro-scale where its organizational attributes emerges physically as heterogeneous spatial pattern. Landscape ecological principle of process influencing structure and vice-versa is revisited from complex systems theory, focusing on functioning at actors level whose aggregated output is also the mentioned spatial pattern. Final insights come from the exploration of affordability of computer simulation tools and techniques, in terms of data availability regarding the representation of urban system dynamic on specific case of consolidation where farmland is converted to urban use in Chillon valley.

This research describe the issues that are connected with conventional approximations to the problem of informal urbanization, and specifically to computational approaches used to represent dynamics of informal house consolidation from a bottom-up approach, suitable for urban planning in northern Lima metropolitan area. Furthermore, it will present an empirically-based computer simulation approach of house consolidation at the fine scale considering composition and configuration of construction state of houses, and assuming social interactions between households within the space of the block. This simulation approach not only allows to detect state transition with adequate accuracy; moreover, it also delivers dynamic properties like non-linear state transition; finally, simulation identify the point in time where the whole block change over from majority precarious to majority developed. These outputs permit to track a differentiated densification trajectory for each small informally developed block or parcel, this fact allows planning.

Model should use data derived from actual composition and configuration of states within the block; these parameters varies in every block and as a consequence related social structure is different between blocks. Model should be calibrated and validated using these empirical data, to assure it is accurate enough to be generalizable and able to replicate similar cases of agricultural subdivision and subsequent densification. Generalization of the model through selection of specific parameters that can be retrieved from real world, permits application to similar locations across agricultural valleys in Peruvian coast with analogous house and block spatial layout and construction attributes.

The presence of interacting neighbors (constituted as social network within housing block space) influencing decision-making is a plausible operation according to social influence theories (Moussaid 2013); thus, it can be hypothesized and used to replicate the relevant dynamics observed in real case of house consolidation in the urban fringe of Lima metropolitan area. Relationship between social interactions and spatial processes at micro-scale during consolidation is assumed as a consequence of proximity and considering that households constantly monitor house conditions in the neighborhood. Therefore, perceived presence of houses in higher states of construction would play a causal effect of influence in promoting state transition in those non-consolidated houses. To make it possible to evaluate hypothesis on influence, consider a simple model of a urban social network at the scale of the block; at this level, social interactions between households are determined by household socio-economic status, which in turn are based on house construction state. Thus, as a result of influence upgrade decision spreads across social network making physical space to improve. To make it possible to test this hypothesis a model is implemented by computational means, providing the ability to conduct simulation of the dynamics of consolidation process; at the core of this analogy upgrade diffusion is formalized though simple but empirically generated and theoretically sound state transition rules. Systems approach using a computer technique called agent based modeling helps to address social and economic issues at the actor scale by simulating individual or community involvement in local decision-making. Taylor et al. (2016) value the use of agent-based models to address complex urban issues, moreover they favor this approach because it is useful "to describe real-world policy situations, where formal analytic modeling reaches limitations of tractability". This research is based on a framework composed by a sequence inference-experiment-test, that fits to the notion of complex system operation. Retrieving actual data on individual households can be used to describe the physical state of housing units and relate it to socio-economic variables. However, frequent measurement of individual physical variables is not possible due to financial constrains to perform field work continuously. For this reason this study aims to generate the general model of consolidation under characteristics observed in Chillon valley. Particular spatial patterns of informal urbanization appears in decentralized spatial development, which configures this specific process at Chillon valley. The methodology should start with data acquisition at bottom level of urban structures, the to explore plausible interactions between households, considering agents whose socio-economic attribute is based on its physical construction state. These interactions are believed to be responsible for the observed emerged spatial structure at upper levels. An hypothesis argues that physical characteristics of houses have direct effect on interactions at household scale that influence upper scale land pattern. This hypothesis further discuss if relative nearness of developed houses have important influence on house improvement. Identified housing units are going to be categorized according to physical attributes related to its state of construction; therefore, socio-economic objects are the base for elaborating a network that represents spatial and social interactions.



(a) Barros (2004)　　(b) Augustijn-Beckers et al. (2011)

Figure 8: Models of informal urbanization

2.8 State of the art

Peruvian local-scale studies about the effects of single-family house consolidation on upper scale structures of the city such as densification of blocks have barely been addressed in literature and seldom recognized in Municipal Plans; moreover, dynamic social and spatial components of consolidation system have not been integrated under a conceptual framework that recognizes its dynamic nature. In their study of Lima urban self-management in relation to informal development and self-help construction, Tamura et al. (2014) pointed out the link between these two dimensions, identifying autonomous individuals working out at bottom spatial scale. In general, studies of house consolidation in Lima have been conducted at micro-scale; these in-deep surveys of households explore the causes of house improvement, without observing explicit social and spatial context and outcomes surrounding these household decisions; finally, spatial settings or scope where these studies are carried on are not related to sub-division of agricultural land as observed in Chillon valley. The joint practice of urban planning and social studies together with a focus on the aspect of independent self-help construction and house upgrade decision-making, has been barely discussed and researched for the case or urban development in Lima metropolitan area. However, integration of social interactions and the correlated spatial processes mainly at micro levels have been a topic of suggested by Saez et al. (2010) who recognizes micro-scale elements as the origin of urban fabric in informal settlements of Lima.

Barros (2012) states that informal urbanization is a spatial phenomenon of social nature, and also indicates that an important characteristic of this phenomena is the process of house consolidation; following these considerations, she investigated growing patterns at macro-scale using agent-based models and simulate the formation of informal settlements in the periphery of the cities in Latin America (Figure 8). Her model called

Pheripherisation spans a long term period of urbanization from initial occupation of land towards recognized later stages of urban decay and gentrification. It uses succession and expansion model of Burguess and includes also a module of consolidation; however, focus is at macro-scale and outcomes are not spatially explicit (Roy et al. 2014). Results from simulation show spatial patterns in a grid where urban poor settle at urban peripheries; this pattern is confirmed by empirical patterns at city scale; however, both as scope of research is to explore and reproduce general spatial patterns following specific properties of urbanization in Latin american cities, model is neither oriented to determine exact location of informal settlements nor determine specific stages of consolidation at a given period. In the other extreme of modeling efforts of informal urbanization, Augustijn-Beckers et al. (2011) developed an agent based-model to simulate individual houses growth within a informal settlement in Tanzania during a five year period (Figure 9); the model replicates occupation and consolidation of houses into an irregular parcel. Model is constructed using field survey to retrieve information; three rules are suggested to be driven the process: Extension (occupation), Infilling (within the parcel), and Enlargement (of net build area). In this case spatial dimension is vector-based and micro-scale, this model replicates accurately the footprint of informal expansion but does not consider intermediate stages of consolidation.

While in the first case the model is build to be general and considering explicitly a theoretical foundation, the second model uses direct empirical data and heuristic rules to design the model and to calibrate and fit it to specific conditions of a single settlement, and generalization is not part of stated objectives. Differences between these specific models points also to macro-scale focus in the former and micro-scale in the later. Despite these differences both approaches recognize the necessary role of individuals in the creation of space, specifically in informally developed settings. Although details and research objectives generate the difference between described approaches, both models coincide in what (Portugali 2016) argues: "cities are composed of material components and human components. As a set of material components alone, the city is an artifact and as such a simple system; as a set of human components (the urban agents) the city is a complex system".

Theory of complexity applied to urban systems treats cities as systems whose focus rather than analyzing aggregated data and elements, has changed to the recognition of its evolving and continuously changing nature, that is characterized by the emergence of structures from individual interactions at the bottom level (Batty 2005). These socio-spatial features make more appealing the use of spatially explicit cellular automata and agent based modeling principles and techniques. The challenges of this shift of focus to individuals and individual level processes involve validation and availability of data at individual scale (Batty 2009). Thus, this bottom-up approach offers great potentials on exploring micro-scale dynamics that are driving process at macro level, whose emerging behavior patterns and temporal trajectories are considered useful for informing and replicating those contingent events and contextual circumstance surrounding those interactions in the urban space. Therefore, the use of empirical socio-spatial data at small scale offers the possibility to replicate urban systems from the bottom-up, in order to better understand its functioning and evolution, and through expanding its prediction capabilities, generate future scenarios for policy and planning. Since modeling of informal development has been increasingly used on urban studies, Roy et al. (2014) made a review of six existing computer simulation models that are "designed to understand slum formation and expansion"; these authors recommends "developing cell-based models as prescriptive and useful tools for real world situations"; even they suggest "the use of ABM to describe and understand slum formation is still rather new". Moreover, in order to enhance the ability to predict emergent patterns and recognizing "the importance of accurate real world data and the high level of realistic spatial data representation to achieve a realistic model output", they recommend the following directions:

- Provide "model's ability to handle spatial resolution" and "to represent specific processes and states in a spatially disaggregated manner"
- "it is critical that a model simulating urban dynamics employs a spatial resolution that fits the context of urban areas in developing countries"
- "it is also important that a model allows for continuous and multiple time steps because informal settlements expand continuously and could follow different stages".

Moreover, use of empirical data to establish initial parameters and conditions is advocated; however, these authors recognize the fact that "collecting empirical data from developing countries is extremely difficult", and "the lack of data limits the ability to validate the spatial pattern" that causes reliability of model predictions to suffer due to uncertainty in model inputs and parameters. To address this issues (Roy et al. 2014) suggest that "a robust model should account for the lack of data by using proxies". "In many (if not most) cases, explicitly representing aspects of both physical and social space will be necessary in order to capture the outcomes of observed social processes (including those of spatial distribution)" (Edmonds 2006); this author argues that physical and social space should be represented together, to make it possible to capture the outcomes of observed social processes including its spatial distribution. "Individuals in a particular region of social space share the same physical environment and a set of beliefs, values and practices that transform this physical environment into a social environment" (Latane and Liu 1996). "Inferring friendship from proximity requires the additional information about the context of the proximity (location and time)" (Malik et al. 2013). "The aim is to reconcile the fine spatio-temporal evolution of the social network with the coarse grained structure used at large-scale population level" (Cattuto et al. 2010). "Notably, the wide field of spatial analysis barely mentions complex networks as it rather puts strong emphasis on econometrics" (Ducruet and Beauguitte 2014).

2.9 Scope of the research

Study on the physical improvement of houses is approached from the bottom-up, addressing the dynamic nature of consolidation, as well; the aim is to retrieve and manage individual data on houses, then to simulate interactions that generates emergent state transition trajectories across space and time; to analyze output from experiments to validate it; validation aims either to compare output against actual data, and to identify complex features in the process, like path-dependence and self-organization, that once addressed provides reliable representation of the process and potential to predict future conditions. Specific objectives of this research are:

1. Perform a systematic categorization of informal housing objects at block scale using high resolution imagery;
2. Identify and describe informal houses as geographical objects and relate this physical components to the social structure at bottom scale;
3. Simulate house development incorporating observed state dynamics within blocks;
4. Validate simulation outcomes;
5. Discuss the relevance of the analysis via simulation and its purposeful implications to urban planning at local scale;

Contribution of this research is the elaboration of a general model of consolidation at micro scale that could be applied to any block that is involved in consolidation considering regular layout and availability of data on construction state at individual level. This micro-scale approach provide an innovative process-based focus to the study of informal urbanization in general and house consolidation as an particular.

2.10 Hypothesis and assumptions

Main hypothesis states that decision to upgrade a given house is dependent on the state of surrounding neighbors. A first assumption is that households perceive and monitor constantly the state of surrounding neighbors. Based on social theories, it is also assumed that the whole system is observable at block scale by state attribute, which can describe the system operation. Another important assumption is that combined individual spatial and physical variables influences house consolidation under informal development conditions. Finally, it is considered that informal urbanization is the actual and most prominent driver of urban development in Chillon valley; as result of its impulse and lack of control, agricultural parcels in Chillon valley are decisively becoming urban.

3 Theoretical framework

As Robinson et al. (2007) recommends, an appropriate approximation to spatial problems is through an empirical approach, which should be oriented to capture micro-processes that are producing change; moreover, these authors advocate the use of computer simulation to make "defensible representations of micro-processes". An additional element that should be taken into account is the social structure evident at micro-scale; as Peterson et al. (2014) recognizes as well, "many individuals and groups made decisions everyday that shape the landscape, and in turn the changes in the landscape shape human decisions"; continuous and dynamic feedback operates in this socio-spatial system, where actors of a cultural landscape are influenced in its decisions by social attitudes and preferences, and by public normative and bureaucratic rules (Jackson 1980). Thus, "the idea is to use computer simulations with human like agents in order to study how aggregation of individuals leads to complex macro behavior" (Berger 2001); in doing so, theory can explain rules of agent behavior (Berger 2001; Robinson et al. 2007; Caillault et al. 2013). Therefore, urban growth model features should include process-based and oriented to simulate individual agent decision; it was observed by simulation that processes at the individual level leads directly to policy and strategy (Batty 2005) thereby, at policy level model could help to answer this ultimate question: "what are the constraints on human behavior and how do we understand them to promote change in individuals, communities and institutions?" (Harden et al. 2014).

3.1 Urbanization as complex system

"As a set of material components alone, the city is an artifact and as such a simple system; as a set of human components the city is a complex system. It is the urban agents that by means of their interaction transform the artifact city into the complex artificial system city" (Portugali 2016). "Dynamism and growth are two of the elements which characterize most urban areas; they may in some instances be a difficult or almost intractable task without tools which embrace their complexity" (Barredo et al. 2003). The theoretical foundation of current research is directly related to the paradigm of interpreting urban phenomena as a complex adaptive system. In doing so complexity theory provides the framework that delineates the keys and assumptions that permit to formalize informal development and consolidation processes at the very bottom scale of houses and blocks. In this sense important concepts that arise from this approach are: self-organization, emergence and path dependence, which are going to be used to build the methodology and to interpret the results.

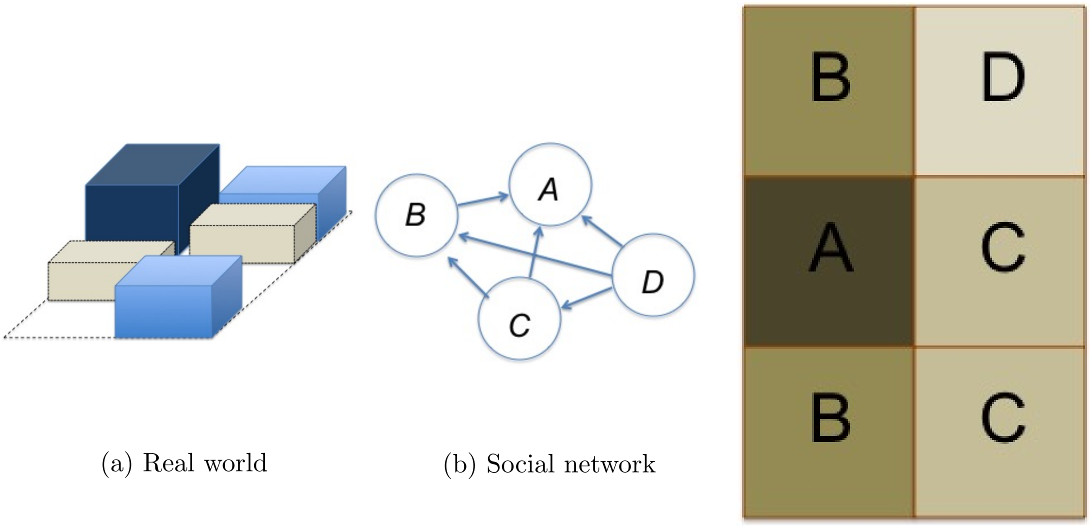
The use of complexity concepts is not new in urban studies; as Batten (2001) suggest that as "cities and regions can self-organize, to understand the extraordinary macroscopic pattern and structure that cities and systems of cities can embrace, we must look into the non-linear character of agents' interactions". Therefore, the object of study is the system composed by individual or individuals whose simultaneous actions over time and space (the other components) have direct effect on urban land use dynamics (Barredo et al. 2003). "Science is gradually getting used to the fact that complex systems are built from the ground up, that the most possible (in fact the only possible) strategy for the development of complexity is coordination of the parts at the most local level" (Batty 2005). This focus at bottom level of objects in the system allow the researcher to investigate the primary causes that are going to cause emergence of new objects in the upper spatial levels. At this point, it is important to include and mention one important methodological issue that arises from observing, implementing, and analyzing change along the time, employing information retrieved from visual imagery; the issue is that "the patterns obtained from remote sensing data usually represent the complex aggregated outcomes of many different individual processes, making it difficult to disentangle the effects of different variables and trends of interest" (Herold, Couclelis and Clarke 2005). In addition, (Lee 2003) observes that "in an urbanized environment, the geographic pattern of residential development is a complex phenomenon to model quantitatively". In order to address this issue, a recent article by Barros (2012) acknowledges the usefulness of complexity approach, mainly because the inherent features of independent and decentralized growth and resultant spatial heterogeneity that characteristics informal development can be handled by assuming simple rules that operates at individual level and generates spatial outputs at an upper level. She also noted that the bulk of the housing stocks in Latin American cities now consists of upgraded (or in the process of upgrading) low-income residential areas, with a large number of spontaneous settlements, and explores a straightforward explanation of this fact by simulating individual decision-making and analyzing spatial outcomes.

"A complex system is literally one in which there are multiple interactions between many different components" (Rind 1999). "The agents within these systems are heterogeneous (think participants in a market economy or molecules within a cell), and their behavior is influenced by the type and quantity of other agents nearby" (Adami 2012). Complexity theory is a scientific field that addresses the interconnected nature and emergent properties of physical systems that exhibit non-linear trajectories in their behavior and production of outcomes along time. A complex system is an information process object, which have a robust structure and adapts to environmental circumstances without any central control unit. Internal behavior on agents can be defined through qualitative analysis of its physical characteristics (Valbuena et al. 2008). "For urban land use modeling, it can be considered that the highest resolution data is typically at the scale of cadastral lots" (Jjumba and Dragicevic 2012). "Common to all studies on complexity are systems with multiple elements adapting o reacting to the pattern these elements create" (Arthur 1999). "The behavior of complex adaptive systems is always generated by the adaptive interaction of its components" (Holland 2014). The agents adapt their attitudes to the attitudes they find in their neighborhood according to the degree of influence of their neighbors (Troitzsch 2015). Additionally, Holland (2014) suggest that the hierarchical structure characteristic of Complex Adaptive Systems is the outcome of particular combinations of agents at one given level, which itself aggregates following non-linear processes towards constituting new agents at the next level up. A set of basic rules of adaptation of householders to the changes in the surroundings, can be established under the following criteria: avoid be different from others and keep difference respect to the average state of development in the block until a threshold of adjacency or distance is passed. It is progressively acknowledged that a comprehensive and quantitative understanding of social systems phenomena in general and urban systems in particular, whose processes are also related to resulting and changing spatial structure, can be explained through complex systems theory (Batty 2005, 2012).

"Path dependency is an empirical category, an organizing concept which can be used to label a certain type of temporal process" (Kay 2005). In terms of understanding house consolidation process as path dependent, state transition decisions made at the initial stages are credited to build a preliminary spatial system that is necessary to consider in subsequent decisions: they can act as structures that can limit or shape available options at a given time step. The establishment of a set of initial parameters in the early period of simulation under a particular rule is limiting the options of future spatial configurations. Change of state consist of additions to the initial composition which remains influential along the time steps; therefore, the choice of each subsequent state composition (and configuration) is determined by early house allocations within the block space; then, consolidation progresses non-linearly towards more dense build space. Once the system operates under the a consolidation-driving rule provoke the emergence of complex trajectories in the state transition steps of the block; change in composition and configuration has come in the form of the addition of new finished houses to the dynamic block system. "Path dependency encourage explicit attempts at dynamic analysis. In this sense, dynamic means that time is an independent variable in the explanation of change. This contrasts with comparative static explanations of change and development where time, if it is considered at all, is simply a change in initial parameters or an exogenous shock" (Kay 2005).

3.1.1 Informal development as complex system

Informal development for residential areas is a well recognized provider of housing for urban poor; its importance as a generator of growth in cities is already accepted as well; its role have been particularly determinant in shaping Peruvian urban policies in the last 60 years (Fernandez-Maldonado and Bredenoord 2010). This topic has also been dominating both academic and governmental discourse on informal settlements even at international forums like UN Habitat, and therefore has been considered while addressing the housing issue in developing countries. Along with recognizing the whole informal supply system at macro-scale policy levels, focus and implementation efforts go deep towards the micro-scale by identifying the role of individual households in the progressive improvement of conditions in houses and neighborhoods. Physical improvement is made through self-help building, which is a common strategy that households adopt to afford house in relation to its financial means and housing needs. Self-managed urban planning is a planning approach that acknowledges decentralized and self-organized urban growth from the bottom level of urban space; Stevanovic (2015) argues that "this is not urbanization seen as the artificial movement of scientific-design committees in white lab coats, but urbanization understood as a process that encompasses different narratives, interests, and ultimately, the role of individual choices in the development of the urban



(a) Real world

(b) Social network

(c) Block lattice

Figure 9: Analogies of diverse spatial and social structures in the block

realm".

Different construction states of houses within the space of informally developed block are assumed to generate tension between neighbors, which is producing influence on households' decision to upgrade their houses. These bottom scale social interactions are hypothesized to cause spatial processes of block infill and densification across the spreading urban fabric. Dynamic social interactions at bottom urban level are credited to provoke emergence of spatial structures located on upper scales in Lima. Social interactions due to proximity allow influence and diffusion mechanism to drive decision-making processes in the consolidation activities. Interactions are performed between households, and state upgrade in houses is driven by perceived higher states in surrounding houses; thus, working hypothesis express that household decision to upgrade its house state is influenced by the condition of neighbor houses in the block. Thus, it is assumed that consolidation dynamics at the scale of houses relies in the influence that households with higher construction state (higher status) exert on others within the regular layout of the block, which is an spatial feature characteristic in informal developed areas in Peruvian coast.

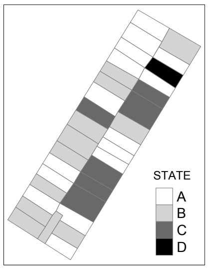
3.1.2 Ontology of housing block

In order to ensure a rigorous geographic representation of housing-related units, ontologically-derived concepts derived from Set Theory provide definitions of houses as parts and the block as the physical compound they form (Figure 9); for that reason two important concepts are presented: the membership relation and the inclusion between sets; the sum of houses and lots area is equal to the block area, this fact gives a strong membership and inclusion relationships that can be later studied via the concept of adjacency. Complementary to spatial characteristics, it is assumed that there are transitive relations of adjacency between all the lots or houses located in the block, for example, house 1 is related to adjacent house 2, and house 2 is related to adjacent house 3, then house 1 is related to house 3. The extent of his transitive relation is useful to support assumptions on spatial-based social networks where the number of neighbors (k) are being accounted in the spatial analysis.

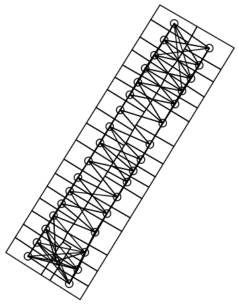
Proposed study of consolidation process is based on relationship between neighbors located within the space of the block. This approach is rooted in the concepts of Opinion Convergence and Social Influence expressed mainly by Degroot (1974), and Festinger (1954); the focus of these theories is on the mechanism of influence that social groups exert on shaping the individual opinion; in addition, Social Influence theory explicitly explains the tendency to adjust ones' opinions in such a way as to become more similar to ones' interaction partners. These concepts are suitable for the proposed approach on replicating consolidation because it is expected, that as a result of influence, all houses will reach consolidation at the end of the process.Within the complex temporal and spatial patterns that the process create, it is important to remark the occurrence of path-dependence; if individuals value the characteristics of their neighbors, then their neighbors characteristics are correlated with their own (Ioannides 2010). For that reason a continuous operation of this bidirectional mechanism of permanent comparison between neighbors are credited to provoke emergent path dependent trajectories on each house, whose aggregated patterns are reflected in block spatial composition and configuration at each time step. Galster (2001) observes that key actors influences the flows of resources driving development, he states that the stock of attributes constituting neighborhood at any point are produced by flows of resources and these flows will be governed by perceptions of key actors.

3.2 Social interactions and spatial processes

Edmonds (2006), suggest that physical space can be used as a proxy for social space; proximity and adjacency in the arrangement of houses into the space of the block permit to assume and explore interactions between householders that are involved in upgrade decision-making. The physical housing system is composed by several houses in different states of construction, which are clustered at the scale of blocks; interactions between households at each categorical state is represented as species interaction within the block (Figure 10). The composition of species (construction states) inside the blocks is dynamically changing due to rule-driven interactions; along with explicit rules of interactions, the concentration in houses of the same state influences the likelihood of the encounter between them, therefore the influence may be modeled including a stochastic component. "Unfortunately, the necessary data about the target system is often lacking, therefore you have to use models in order to reproduce realistic spatial distributions of the population" (Amblard and Quattrociocchi 2013). "The research often did not measure phenomena directly but rather the ability for the urban environment to support



(a) State configuration (year 2006)



(b) Non-directed network

Figure 10: Spatial and social structures in Block 1

phenomena of social interactions" (Speranza et al. 2015). Urban theories that account for interactions at the bottom scale of houses were originally related to study real state requirements for location and valuation; Batty (2009) cites some housing market models elaborated in the seventies, that features individuals, market processes and developer decisions. Moreover while conceptualization of the individuals and their interactions became popular among different disciplines in social sciences (including urban planning), this modeling efforts faced challenges related to lack of individual data and more explicit theories to explain the variety of dimensions that urban development encompasses (Batty 2012).

Composition and temporal changes in house states shows heterogeneity and a complicated network of adjacency dependent on the number of neighbors of a given house. As the houses interact its physical attributes are being modified through a process called Coevolution, which is operationalized by coding its attributes and recombining these property-related codes that results in a new recombined coding set; thus the number of finished houses increases along time following optimization rules. It is important to remark that the results are non deterministic, and depends on either in the number of houses at the same state in the surrounding neighbor and in the application of conditional rules at these changing context. In a simple case of encounters between two households, they interact each other and the result is not always the same in every encounter, because it depends also in the state of the neighbors, thus encounters are governed by conditional probabilities, and emergent properties of block structure and growing pattern replicates observed heterogeneity. "Urban change involves transformation in the physical appearance and the social composition of the neighbors" (Naik et al. 2015); "at street scale neighborhood social and economic factors are far more likely to influence change than they are in a city wide or regional metropolitan scale" (Dietzel et al. 2005).

3.2.1 Neighbors and upgrade decision

"To understand how collective order arises from seemingly random fluctuations, we must note how agents choose to interact with other agents and with the environment" (Batten 2001). Clearly delimited and regular shaped housing block is a lattice-like space composed by cells that corresponds to houses in different states of consolidation; thus a result of proximity interactions between neighbors are plausible (Saez et al. 2010). Housing units are credited to be geographic units occupying a space and possessing physical attributes, which have effects upon other similar units (Casati et al. 1998). Along the process of house consolidation the operation in the system at block scale reflects individual decisions on house construction that leads to the upgrade of its state; thus state transition (decision to upgrade) is driven by a proposed hypothesis that considers surrounding house conditions. Robinson (2007) suggest that when analyzing trajectories of land use change it is useful to test hypothesis about relationships between: a) agent decisions, and b) a range of spatial and contextual variables.

The study of interaction is rooted in the concept of Opinion Convergence as expressed by Degroot (1974) and Moussaid et al. (2013); the focus of this theory is on the mechanism of influence that social groups exert on shaping the individual opinion converging towards an average at the end of the process. Interactions are performed between households and here is where influence operates on households' decision to upgrade its house state by observing the average condition of other houses in the block. It is suggested that informal urban growth is based on individual interactions within mixed spatial composition at block scale; informal development context makes the process to be complex. Within this complexity it is important to remark the plausible correlation between their states along the way towards total development; "if individuals value the characteristics of their neighbors, then (as an outcome of their choice of location), their neighbors characteristics are correlated with their own" (Ioannides 2010). It is also possible that already developed houses have key role in influencing upgrading of other houses; Galster (2001) observes that key actors influences the flows of resources driving development, he states that "the stock of attributes constituting neighborhood at any point are produced by flows of resources and these flows will be governed by perceptions of key actors". Finally, regarding the structure of underlying social system in cases where data about it is lacking or unstable like in recently stablished social systems, Latane and Liu (1996) suggest that "when there is no basis for order in the social relations among people, the structure of relationships may be random".

3.2.2 Complex interaction system

At bottom level households are adapting (changing states) according to the dynamic composition and configuration they are creating within the block. The overall structure of agents and interactions is an information process object whose adaptations does not follow a central control. It is time to introduce another dimension of development operation, it is the interaction between households that is leading to the generation of a complex interaction system, from where a decision to develop is detected by spatial and physical conditions of houses present into the block boundaries. In order to build the mentioned mechanism from individual data, lets imagine interactions between nodes with a fixed number of connections to other nodes within the block; as the mechanism of influences operates resulting configurations show detailed information on development process between the individual houses at each time step. The type of relationship this research addresses is the one that provokes emergence of state configurations at block scale, caused by individual behavior by the means of house state at the bottom scale. In this sense the operation is going to be represented by a non-linear and stochastic state transition function that includes physical (state), spatial, and probability variables that conditions the emergence of specific pattern.

Systematic interdependencies exists between internal objects in the block; a well-selected subset of variables could contain sufficient information about the rest of variables. A system is called observable if we can reconstruct (synthesize) the complete internal state of the system from its outputs (Liu et al. 2012); the system is observable from sensors, which should comply not only necessary but sufficiently criteria. Representation of the internal structure of the system composed by houses and interactions is required to identify the relevant outputs that describe the system; therefore, the focus is dedicated to identify the sufficient and necessarily outputs that describe the dynamic operation of state transition in houses, considering it a complex adaptive system. It is assumed that the whole system is observable at block scale by some features identified through imagery, which can describe the system operation. In the block-house framework these accessible outputs can be referred to the spatial and structural attributes of the objects; these data enables the estimation of the internal scale from accessible outputs via experimentation. The outputs depends on three main variables or parameters: time, internal state of the system, and the influence of the environment (external input). Formal algorithm that represents the mechanism of interrelations include house functions that allows it to detect and monitor of neighboring houses (environmental state), which are hypothesized to influence in the household decision to develop. By seeking interdependences between identified housing units, as a network resembling a social system that uses physical properties of individual houses as proxy of socio-economic attributes. As Holland (2014) states “Networks provide a precise snapshot of the interactions of agents in a complex system at a given point of time”.

3.3 Computational socio-spatial system

Complex systems analysis has become a fascinating topic in modern research on non-linear dynamics, not only in the physical sciences but also in the life sciences and the social sciences (Reggiani and Nijkamp 2009). One of the features of this theory is that it does not focus on static versions of a system but instead recognize the dynamic process of changing spatial composition and configuration of elements in the system and its representation. Consolidation system is a real world systems that operates at a slow pace across years; a virtual representation of this system allow to provide “velocity” to the system, and therefore replicate and predict its dynamic. Thus, computer simulation of such complex systems is suggested not to provide a single representation at a point

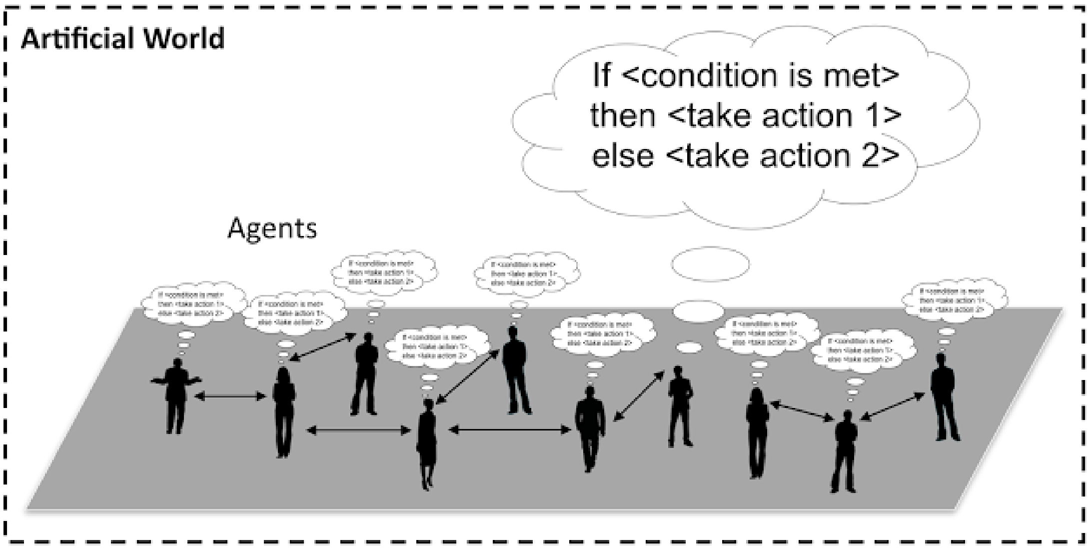


Figure 11: Conceptualization of an agent-based model (Source: Heppenstall and Crooks 2016)

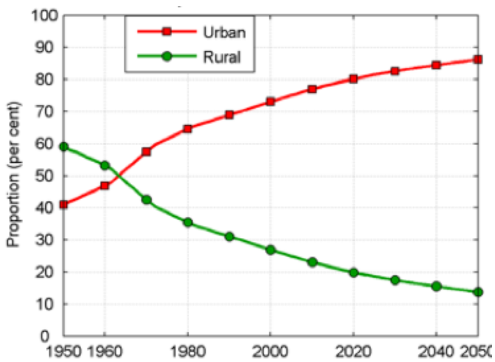
in the time, but tries to obtain several outputs from which provides potential insight of a relevant pattern or law (Vicsek 2003). Computer simulation allows using techniques and tools to build the model and define initial parameters from which the agents start behaving independently and consequently producing spatial patterns. Results are not focused on explaining the actual phenomena in study but outputs of several simulations are expected to provide some quantitative clues about the process that actors follow according to the established initial parameters of the model.

Therefore to make it possible to address the above-mentioned problem of describing and interpreting the complexity of informal development at bottom scale, a theoretical as well as methodological constructs called Cellular Automata (CA) and Agent-based models are going to provide the spatio-temporal setting for experiment and analysis. “Cells represent the basic units of spatial representation, which we assume are indivisible” (Batty 2005). “CA provides a computationally efficient technique for investigating the general nature of dynamical systems” (Straatman et al. 2004). “Growth patterns can emerge from the transition of states of individual cells” (Liu and Feng 2012). “One of the most potentially useful applications of cellular automata from the point of view of spatial planning is their use in simulations of urban growth at local and regional level” (Barredo et al. 2003). “In contrast to macroscopic land modeling, classical CA is a purely microscopic approach” (Wu 2002). CA models are thus credited to be capable to produce dynamic spatial models since their analytic basis is not only the cell values on each case, it includes the neighborhood cell states as well; in addition, the interactivity of the model produces an approach that meets the realism needed for simulating actual urban processes (Barredo et al. 2003). “Cellular Automata (CA) based models have a high aptitude to reproduce the characteristics of urban processes and are useful to explore future scenarios" (Barreira et al. 2015). "Agent-based models (ABM) can explicitly formalize simple to complex representations of the behavior and cognitive processes of actors who make land and resource use decisions within the system" (Robinson et al. 2007). As Box (2002) argues, "a typical use of ABM is to simulate scenarios where large numbers of individuals are inhabiting a landscape, interacting with the landscape and each other by relatively simple rules, and observing the emergent behavior of the system (population) over time". The space of maneuver of these actors is located into a micro scale network of relationships and its related and explicit spatial context; influence comes by both the same level and the superior scales sets of allowances and constraints. Thus the problem is to find empirical data on heterogeneous, representative, and proportional groups of actors to represent those that intervene in the actual system; to make this selection it is important to take into account "the scope and scale of analysis, as well as the degree of heterogeneity one wishes to capture" (Robinson et al. 2007). By focusing on large scales research and literature of urban development offer partial understanding of the informal growth in cities. Building computational models of urban growth at bottom scale offer a quantitative approach to replicate the dynamic nature of consolidation process. "The sheer choice of using an ABM to represent a target system implicitly indicates a purpose to model the underlying generative mechanisms that are governing the dynamics" (Hassan et al. 2013).

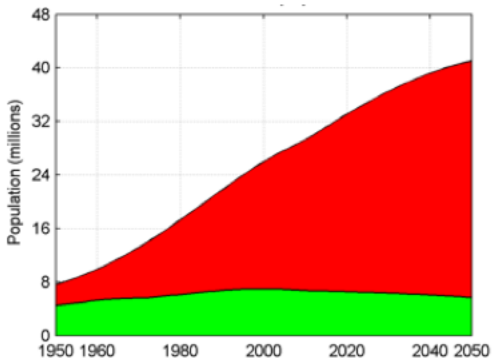
4 Case of house consolidation at Chillon valley

4.1 Urbanization in Chillon valley

Chillon valley belongs to Lima metropolitan region, this location near to urban services and facilities has created a housing market, conditioning both supply and demand for houses. Increasing urban population in Peru (Figure 12) has created a steadily increase in demand for houses, and Chillon valley has perfect conditions for urban growth; thus, population also has grown in two of the administrative units of Chillon valley: Puente Piedra and Carabayllo (Figure 13). As the country become urbanized agricultural surface decreased sharply in Lima region during the past century; this tendency is also observed in Chillon valley (Figure 14). Natural conditions of the valley (flat land a water supply) has been attracting people, first to agricultural activities; agricultural production is still performed on clearly delimited spatial units: the parcels; these parcels are also the units where land conversion to urban uses is primarily performed. Free market forces along with the lack of enforcement in regulation has been driving subdivision at parcel scale. Moreover, radical changes in the norms that regulate the ownership and tenure of agricultural land, have created demand for urban purposes, at the level of small land owners who are the majority in the valley (De Soto 1989).



(a) Urban-Rural population



(b) Growth trends

Figure 12: Urban population growth in Peru (Source: UN Population Bureau 2014)

It has been identified long term process of urbanization at parcel scale; this process has two stages: a) Parcel Subdivision, when agricultural parcel is subdivided to small urban structures: blocks and lots; b) Residential Consolidation, when lot is occupied progressively for the housing unit. Thus, spatial phenomena affects several individual parcels that converts from agricultural to urban; under subdivision independent smaller units appear creating new heterogeneous spatial organization and growing pattern towards consolidation and densification. Internal street layout, urban facilities, and aggregation of houses are some of the explicit outcomes resulting from this process of subdivision. Former agricultural parcel, as observed in cadastral maps (2008) and imagery (2002), once developed, keeps on perimetrical access roads. which have became primary

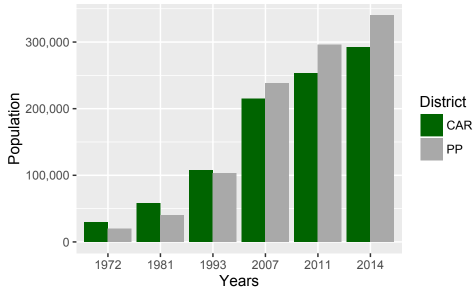
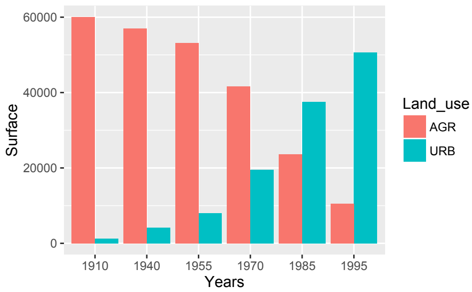
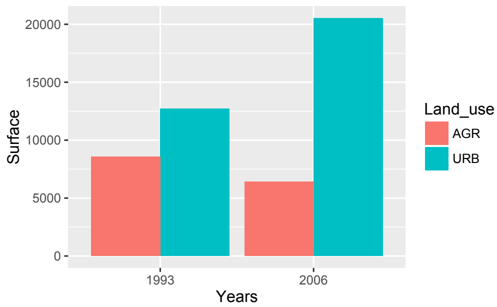


Figure 13: Population growth in Puente Piedra (PP) and Carabayllo (CAR) municipalities



(a) Lima region



(b) Chillon valley

Figure 14: Changing surfaces (in ha) of Urban (URB) and Agricultural (AGR) land uses (Sources: Ismodes (1997), INEI (1993, 2006))

neighborhood streets that allow internal access to blocks resultant from subdivision.

The nature of spatial objects is approached focusing on the structure and processes of informally developed parcels and its spatial configuration. Thus, this study aims to identify the nature of the three main physical components. An elucidation of its member relationships and its inclusion into parcel boundaries are the primary goals in pursuing individual data. Spatial urban objects appear with the event of subdivision; this event considers different scales of structure formation, where each particular parcel subdivision emerges into a spatial fragmented structure at valley scale; parcel data is divided first to configure blocks, then blocks are subdivided into several housing lots; this process creates separate parts whose structural characteristics can be used to describe agents and environment where they interact.

With the obtained data of properties from parcel scale it is possible to create a system and establish a relationship between the components of the system: Block space and householders. Manipulation of the model is oriented first to test the effect of informal development at upper-level; a second round of simulations are oriented to test hypothesis on the mechanism of house development. Housing units are credited to be geographic units (occupying a space and having socio-economic attributes), and moreover they have effects upon individuals (Cassati et al. 1998). Subdivision is the process that creates new geographic units (housing units) that configures the space where interaction between individual households occurs. Social system operation at parcel scale is reflected by individual house construction sparsely allocated into blocks; thus the overall process of land development are based on decision of parcel owners to subdivide and the lot buyer who built its house, both of them legitimating its control over its own private property. Therefore, in analyzing trajectories of land use change, it is useful to test hypothesis about relationships between 1) agent decisions, and 2) a range of spatial and contextual variables (Robinson 2007).

This approach enables the research to focus inside a individual parcels without considering influences of neighboring parcels. However this study considers two important external parameters that affect behavior of the parcel and the agents that compose it; these parameters are the Construction Code, and the land available (housing supply) at a given time.

4.2 Regulation of urban development

Currently, remained agricultural areas in Chillon valley belongs mainly to the administrative boundaries of Carabayllo Municipality. Normative functions of Carabayllo Municipality are: to elaborate and implement urban expansion plans, including regularization and improvement of physical conditions in informal areas. In farmland informal areas develop spatially through parcel basis. A former agricultural parcel change into urban keeping its boundaries; therefore subdivision and house consolidation occupies the same parcel area. Developing area is not providing adequate housing functions as most of houses are precarious and lack of basic utilities and proper urban infrastructure as parks or paved streets. But regular layout of blocks and rural access roads provides the template for physical improvement. Under this context house improvement leads to infilling and densification. Physical and demographic densification represent the conditions against improvement projects are evaluated. The basic components of urbanized parcels are the individual houses, which are being used as exploration objects rather than a predictive piece of information; therefore as Jensen and Cowen (1999) stated houses are "dwelling objects used to measure physical development attributes". These basic housing units are grouped into housing blocks which are major components at the next upper scale; the house or dwelling unit studied belongs to High-density Residential according to the parameters stated by Peruvian Construction Code (2006).

Along with Construction Code, Peruvian Law 29090 regulates urban development and building permission; it establishes a set of licenses that are required in order to formally develop land and construct buildings in urban areas (Figure 15). The main requirements that a developer must accomplish are:

- Land property right title;
- Municipal license of development;
- Zoning agreement;

Figure 15: Formal development in Chillon valley

- Public utilities availability;
- Urban design plan, according to design parameters stated in the Construction Code;
- Environmental Impact Assessment;
- Soil mechanics test.

Control and approval of above-mentioned requisites is performed by local municipalities; once developer is granted permission, he is able to implement one of the following types of residential-oriented development:

1. Conventional, executing urban infrastructure prior selling lots, which consists on laying-out streets and sidewalks, establishment of green spaces, and instilling basic utilities (sanitation and electricity);
2. Guaranteed lot sales, selling lots without any work being started;
3. Progressive, performing sales prior finishing residential related infrastructure without allowing house construction;
4. Simultaneous development and construction, authorizing houses to be constructed along with urban infrastructure.

In the period 1968-1979 and due to the Agrarian Reform Law, the growth of urbanizations in agricultural areas was consolidated; by means of this law, it was allowed to expropriate agricultural estates greater than 150 ha for urbanization purpose, within a period of 5 years; this regulation caused the parceling and the sale of agricultural land for occupation of popular neighborhoods in the lower part of the valley (Calderon 1998). Housing policies entitled since 1990 gives almost entire responsibility of residential housing supply to market operation where a multitude of private land owners who in many cases act as private developers along with licensed real state developers deal with their role at parcel scale which is the piece of land no larger than 5 ha. Market demand is influenced by design parameters stated in the Construction Code for residential development, as suggested by typical lot and block sizes observed in both informal and formal types of development. This market-oriented housing supply explains observed individual behavior in house development and surrounding spatial and social context. Consolidation drives demographical densification and physical infilling within block space. Former agricultural parcel changes through neighborhood consolidation process while keeping its external boundaries; internal structure and functions transformation create a layout of urban super-blocks within the urban fabric in the valley. As driving factors are credited to be interactions within the blocks, densification and infill at upper super-block scale are properties derived from the bottom scale.

"Most EU and US planning systems, aims to promote certainty regarding future development by employing statutory land-use plans for stabilizing and binding the development of land use" (Alfasi et al. 2012). In Japan,urban planning from the 1960s onwards have took place in the form of long-term comprehensive land-use plans with strict regulations for new development aimed to ensure housing units get public facilities, providing real estate corporations clear guidelines to provide residential assets to the market. In Peru, and due to a economically liberal framework, a large percentage of housing supply is provided by informal market; limited effectiveness of regulatory land-use planning for this complex, rapid and densely populated informally developed areas requires an approach to address small scale and heterogeneous nature of its dynamics. Consolidation process provides the basis to investigate this type of urbanization and explain the causes and characteristics that are producing urban fabric from the bottom-up. The significant gap between zoning and actual informal reality in Chillon valley may require other forms of long-term regulations, which are better suited to promoting planning certainty and providing better housing conditions. This gap is being bridged by municipal regularization programs that aims first to grant property deeds and then invest public funds in order to improve infrastructure.

4.3 Parcel subdivision and house consolidation

Residential land development in Chillon valley is informal in the great majority of cases; informal development is presented as an alternative to formal, centrally-planed residential settlements that where dominant in the development of former agricultural land in Lima metropolitan area. The investigation focus at the scale of houses and presents a systematic study of house consolidation or construction state transition in the context of informal development in the period 2002-2015, when population increased rapidly; temporal changes are observed at the upper level of housing blocks where aggregation of spatial units at housing blocks allows to notice more clearly emerging spatial and socio-economic patterns and properties showing independent and progressive development trajectories.

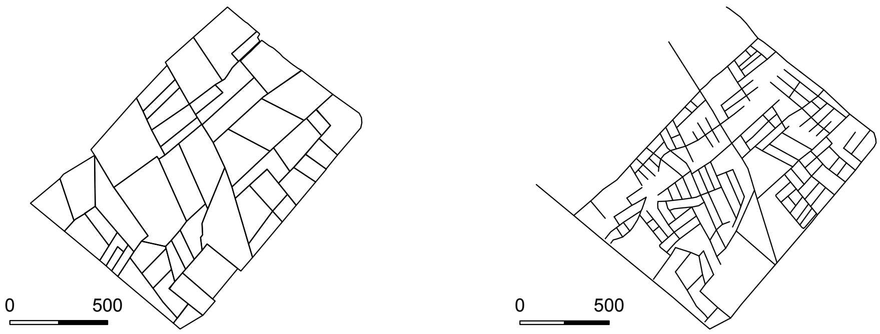
Observing the spatial structure of residential development in Chillon valley two types of residential development have been identified:

1. Informal, which grows first depending closely on immediate housing demand from people with few resources, leading to house allocation and occupation by precarious structures, where the informal developer (former farmer) performs basic land subdivision without investing in urban facilities or infrastructure; and second, progressing the house construction along with urban utilities, reflecting resources availability in the household;

2. Formal, where the housing land parcel is developed completely with urban utilities and infrastructure such as sidewalks or streets prior selling lots to households; thus, the level of occupation is directly related to revenue of developer who incurred in previous investment; moreover occupied houses are rapidly being constructed, reflecting a major income level on the households.

In the case of informal development, the parcel as a former agricultural production unit in Chillon valley is being subdivided for urban uses and therefore being occupied by housing units. At the bottom level of the urbanization process informal house construction is in average lasting several years to culminate (Tokeshi 2005; Barros 2012). Growing density in the increasing urbanized parcel is related to independent house upgrade; thus, progressively expanding population make social interactions and economic outputs plausible due to proximity into the spatially defined urbanizing parcel. Housing associations are common and are in charge of bargaining with local authorities the provision of urban utilities and related services. Individual outcomes are grouped in two types of construction states: finished houses and houses in consolidation; a study on the degree of consolidation in informal constructed houses showed that only 6% of them were in the final stage of completion (1/2 de Construccion 2002). This different performance causes a lag in the state of construction and a random spatial configuration of finished houses at block scale.

Composition and configuration across scales in houses, blocks and parcels show highly diverse random-like spatial organization; this heterogeneous landscape that progresses spatially without central control is result of informal type or housing development that is operated at finer spatial levels. The variety of construction stages at the house scale is generated through a complex functioning that still has not been specifically formalized for the case of informal development at this bottom scale. Current theory of urban growth offers macro perspectives that does not explain explicitly the dynamics of informal development at the scale of houses belonging agricultural parcels in transition towards residential uses. As spatial patterns are changing rapidly, emergent uncertain conditions in future spaces does not allow individual households and public and private



(a) Parcels layout

(b) Streets layout

Figure 16: Urban morphology during informal sub-division

organizations to focus on long term planning of household-related economic issues like utilities fees or taxes, which are directly linked to physical improvement of private and public infrastructure.

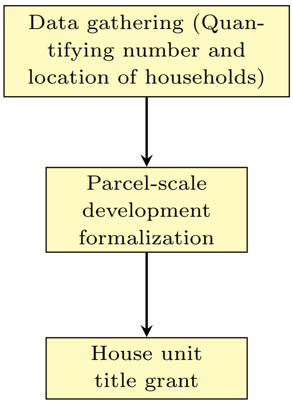


Figure 17: Steps in house formalization or regularization

Informal housing production is notoriously influencing urban development in Peru as it has constituted a large amount of construction GDP in general and housing supply in particular. Informally constructed housing units represented in the year 2009 a 25% of total GDP of the Peruvian construction sector. In Peruvian economy a particularly notorious feature is household entrepreneurship, which is oriented to improve living conditions independently from formal public or private institutions; it is particularly true at housing realm because informal householder cannot afford to finance formally built house (De Soto 1989). Deregulation and privatization provokes informal activities to come out in several sectors of the economy (Maloney 2004). One important characteristic of this activity is that informal housing, as a constructed physical object is finished through a long term process lasting at least one generation; moreover, the physical consolidation process in houses requires the presence of a individual household, which assumes the role of informal house developer, using resources and time to perform its independent activity (Tokeshi et al. 2005).

4.4 Informal land regularization

Land regularization is the process of public intervention in illegally occupied zones to provide urban infrastructure and property titles (Calderon 1998); this policy constitute the core of public interventions on informally developed lands. This process considers a series of steps oriented to incorporate the informal areas to the formal city (Figure 17), which includes not only the provision of property titles and infrastructure, but allows Municipalities the right to levy taxes once this process is finished.

Property Tax on Houses is collected according to Municipal Tax Law 776 (1993) and Tribute Code (2013); under this legal schema Property Tax is levied by local Municipality once a year, and a a primer condition the tax applied to the land and building should be located within an urban area and must have basic utilities installed; one important legal mandate is that sanitation infrastructure development using public budget requires house to be regularized. Thus, tax collection is linked to Regularization of informal houses, and therefore Municipal tax collection seldom applies to informal developed land unless it has property deeds and basic services supply.

5 Research Methodology

The object of study is house consolidation, therefore, research is oriented to explore socio-spatial dynamics within the block, which are driving consolidation process. To test the hypothesis of social influence a computational analogy is devised for further simulate and experiment the dynamics and its factors: house is the element that is being changed, through the “force” of influence. A replication of the structure and function at block level, should be able to generate growth and produce emergent spatial patterns at upper scales. An analysis at bottom level is possible under theories based on complexity, bounded rationality and social networks, which acknowledges individual agents, relations and rules governing these interactions. Thus, a first stage of the method is oriented to build an empirically-based model that replicates the spatial and social system, making it operational through calibration and ready to start simulation and growth across time. In order to make replication possible, a clear sequence from visual identification to validation method is clearly stated. Two types of models of interactions between householders are used in order to test influence regarding spatial or socio-spatial factors; first, test spatial adjacency, and second, diffusion through explicit social network. Both cases use specific transition rules that are respectively: 1) updating rule, and 2) epidemic diffusion. Each mentioned models make individual agent to perform decision rules influenced by stablished interrelations.

5.1 Methodology development

General approximation for this investigation is based on establishing a case-specific research instrument that is composed by a sequence of three steps, which considers the following scope (Figure 18):

1. Acquiring fine-grain data using a systematic protocol to categorize construction state at the scale of individual houses
2. Deriving a simple process model of consolidation from empirical spatial patterns, and literature review on household-scale surveys and social influence theory
3. Scaling-up from rule-driving interactions towards collective dynamics of consolidation by means of computer simulation

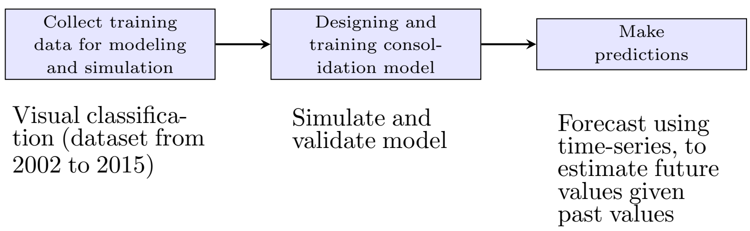


Figure 18: Building and employment of proposed research instrument

A specific process of change in spatial configuration along time regarding the states of houses is targeted at block scale. This spatial analysis procedure is applied in sets of houses already organized into housing blocks. It is important not to forget that the goal in this section is to find interactions between similar objects. Transitive relation concept originated in Boolean algebra is introduced at this stage of the study; it refers to the influence that a neighboring houses have on a given house, whose status is being analyzed in relation to a specific number of neighbors. Outcomes of interactions are visualized in clustering-like processes, which are in the form of spatial patterns emerging from those interactions; this patterns appear when a certain mechanism dependent of surrounding status operates, which is signaled by a indicator or spatial metric. This moment is signaled to the householder who make the corresponding decision; therefore his role as key actor in property development is fundamental. The implications of explained heterogeneous aggregation of houses in the parcel relates to the challenge of fit these newly created space to the formal structures of the city need to be addressed in order to evaluate the systems within an accepted set of city functions expressed by the spatial and institutional framework of city rules. Bottom-up approach is the premise derived from acknowledging first the role of interactions between households, and second that the processes of consolidation and subdivision are bounded within blocks and parcels boundaries respectively. Focus in this bottom level highlights the problem of conceptualization of the objects in the hierarchical levels into parcel-block-house compound. Specifying the compound means describe the spatially-based attributes of the present objects and its interactions.

Computational models are built using empirical data at individual house scale; this adopted procedure permits to conceptualize the models in reference to real world conditions using algorithms that represent construction state transitions, which further allows to calibrate and validate them explicitly according to spatial datasets retrieved from visual identification of high-resolution imagery. Using the categories proposed by (Tokeshi 2005), four classes of progressing consolidation are identified regarding its construction state (Figure 19 and Table 1).

Table 1: Categories of house consolidation.

Class type	Name	Characteristics
A	Provisional	Precarious material, likely to be improved
B	Incipient	Basic structure without light concrete roofing
C	Consolidated one floor	First floor already finished with concrete slab
D	Consolidated two or more floors	Finished with more than one story

(a) Class A

(b) Class B

(c) Class C

(d) Class D

Figure 19: Categories of Consolidation (Tokeshi 2005)

Table 2: Characteristics of satellite imagery employed for classification.

Parcel	Imagery type	Spatial resolution	Year acquisition
1	Quickbird	0.65 m	2002, 2006, 2009, 2011, 2013, 2015
2	Quickbird	0.65 m	Id.
6	Quickbird	0.65 m	Id.

5.2 Micro-scale data acquisition

Procedures to estimate the dynamic conditions of informal development are required to be spatially oriented and reaching bottom levels where houses are located, with the level of precision that ensures modeling and replication. This research is oriented to discover the underlying conditions and mechanisms of urbanization by studying only spatial data retrieved from visual identification using high resolution satellite imagery; employable data is available in visual spectral range as it is freely provided by Google Earth (GE). “Google Earth imagery has great advantages for mapping land use/cover types with good spatial characteristics in terms of geometric, shape and context (e.g., road and river)” (Hu et al. 2013). Moreover, the selection of useful imagery is conditioned by the quality parameters that the imagery provides, mainly absence of clouds; thus, high-resolution satellite images from the following six years have been selected: 2002, 2006, 2009, 2011, 2013, and 2015 (Table 2). In addition to the use of horizontal images, Street View (2013) elevation photos are being used to confirm the number of houses within block and to detect presence of urban utilities servicing houses. Visual image interpretation is used to identify the morphology of the urban structures because it enables to obtain the best taxonomic information and the best geometrical accuracy (Reginster 1997 cited by

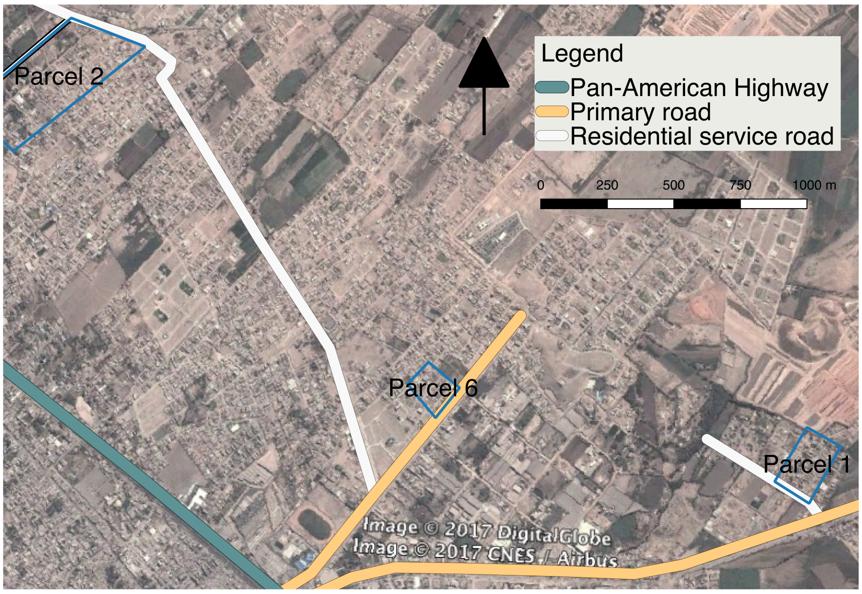
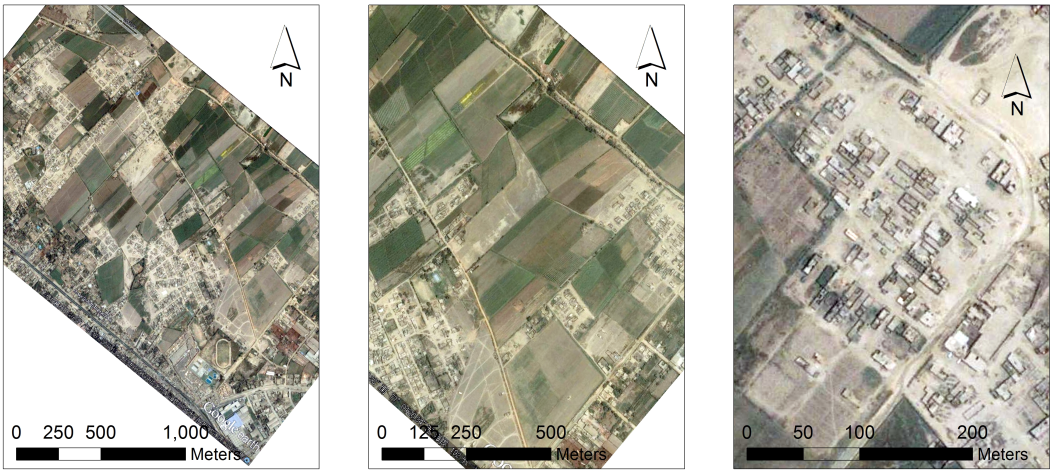


Figure 20: Study area in Chillon valley

Table 3: Criteria to identify visually housing objects.

Object	Tone	Shape	Size	Pattern	Texture	Shadow	Association
1. Lot size	Light gray	regular	small (75-200 sqm)	grouped	coarse	no	residential high-density
2. Vacant lot	light brown	regular	variable	isolated	fine	no	residential high-density
3. Subdivision	light brown	regular	small (75-200 sqm)	regular	fine	no	residential high-density
4. Unpaved street	light brown	linear	short	grid	fine	no	internal access
5. Street pattern	light brown	cul-de-sac	short	grid	fine	no	linked to neighbor-hood
6. Street width	light brown	irregular	narrow	grid	fine	no	continuous access

Puissant and Weber 2002). Proposed method for visual interpretation of satellite images can roughly be divided into two levels: recognition of objects and sampling criteria, and



(a) General areas at urban-rural fringe (b) Similar areas of informal development (c) Single objects (blocks layout)

Figure 21: Scalar approximation to identify informally developed areas

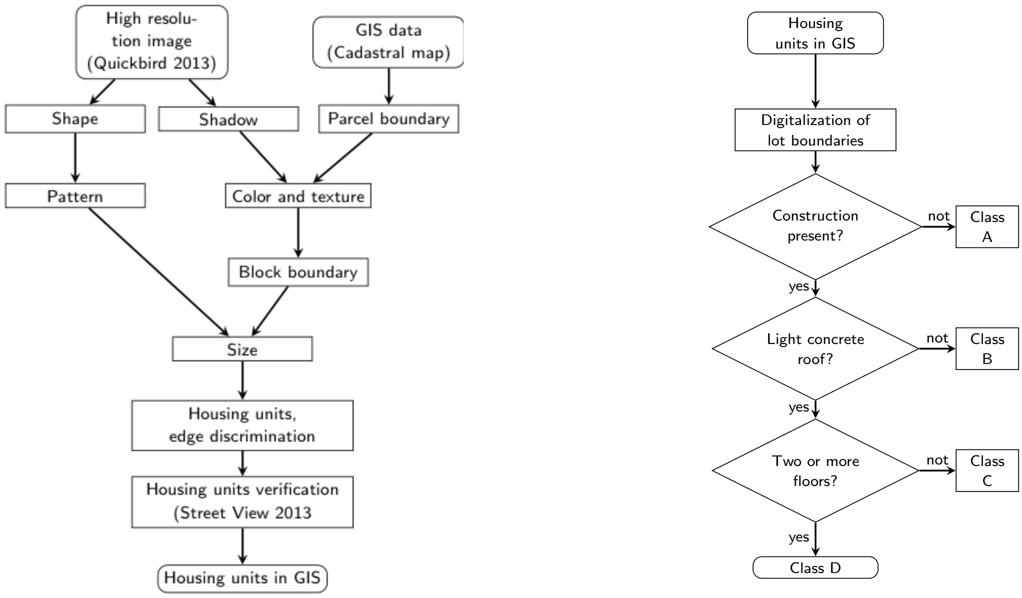
methodological interpretation through a explicitly devised protocol.

5.2.1 Recognition of objects

At a first step of visual interpretation, three parcels are selected (Figure 20) according to its possibility to represent the range of construction states in the observed houses in the context of informal development; parcels are defined as former agricultural areas that maintain its boundaries as they develop. The number of buildings and their state is assessed according to the house consolidation categories presented by Tokeshi et al. (2005). Identification of housing objects relevant to this research should recognize a hierarchical approximation where objects are identified from parcel to block and house scale. Parcels were selected to represent the heterogeneous range of socio-economic status and size composition of internal housing blocks characteristic of informal development; parcels were defined as former agricultural production units from data in Cadastral Map (2008).

Previous to visual identification, each GE image was geo-referenced using ArcGIS 10.1 (ESRI 2012); along with identification, parcel boundary is delimited according to Cadastral Map (2008) or, using rural roads as proxy of former boundaries; sub-parcel objects are identified inside parcel boundary according to sub-parcel selection criteria (Table 3). Parcels that showed informal development characteristics were choose according to the following sampling criteria:

- High land use heterogeneity identified in the sector: housing, recreational, cattle breeding, agriculture.



(a) Housing units (b) Construction states

Figure 22: Visual identification protocol

- small property size, less than 5 ha.
- absence of paved roads.
- development stage of parcel: sub-division.

Hierarchy of visual image interpretation is formally established through three scalar approximations (Figure 21):

- General areas: 1/10,000
- Similar areas: 1/5,000
- Single objects: 1/1,500

5.2.2 Visual interpretation protocol

High resolution analysis allows location of small size houses and features of its structures that provides socio-economic attributes about people living in each house (Jensen and Cowen 1999). Informally developed parcels present characteristics related to subdivision, internal street pattern, urban facilities (sanitation and electricity supply, parks, paved roads, pedestrian sideways, road width), and house state. From the above mentioned indicators it is possible to study the spatial and temporal nature of different types of urban objects and attributes, and describe its relationship. However, as the aim is

Table 4: Interpretation Key of six objects at block scale.

Elements	Block	Paved road	Non-paved road	Concrete roof	Sheet roof	Vacant lot
1. Color	light gray	light brown	light gray	white, light gray	light brown	light brown, dark green
2. Shape	geometric irregular row	linear	linear narrow	regular polygon, irregular edge	irregular polygon, fragmented	regular polygon
3. Size	short length (60-180 m)	short	large	small	very small	small
4. Pattern	polygon, fragmented	grid	grid	patchy	irregular patchy	patchy
5. Texture	hard, coarse	hard, fine	soft, fine	hard fine	coarse	soft, fine
6. Shadow	linear thin	No	No	linear thin	No	No

to identify independent houses and related physical attributes, construction state is targeted for visual identification. Identification of objects is performed using elements of visual interpretation - EVI (Lillesand et al. 2015) as a reference to develop customized criteria used to perform visual interpretation of housing units and house state in Google Earth. Following elements are considered for Consolidation EVI:

- tone and color: light brown, brown, light gray, gray, green;
- shape: regular, irregular
- size: small, big, narrow, variable;
- pattern: grouped, isolated, grid, cul-de-sac
- texture: fine, coarse
- shadow: yes, no
- site, situation, association: residential high-density, accessibility from outside parcel.

Six relevant objects are present in informal places at block scale (Table 4): Block, Paved road (asphalt), Non-paved road, Concrete roof, Sheet roof, and Vacant lot. Last three of the above mentioned objects are used to read the construction state of informal housing units in consolidation; classification process is implemented through a Visual identification Protocol of Consolidation (Figure 22), which uses an Interpretation Key to differentiate houses and its construction states.

Elements Shade and Shadow provides first visual reference to identify informal urban agglomeration in high-resolution imagery; cadastral map from 2008 in GIS format allow to delimitate Parcel boundaries clearly; once setting Parcel boundaries both Color and Texture help to establish the limits of block. Through pattern recognition of objects located into block boundaries an average size of housing units can be detected; these housing units are discriminated between two classes: light concrete roof and sheet roof, discrimination also allows to count the number of units. Verification of total number of housing units and vacant land present at the block is performed using Google Street View photos (2013); house boundaries of each selected block are drawn in GIS (Figure 23).

Figure 23: Digitized lots in Block 2a

5.2.3 Field information on social aspects of Consolidation

While acquisition of empirical data on state is by no means a comprehensive collection for studying social aspects influencing consolidation, heterogeneous attributes of state provided the necessary data to find transition patterns and implement a modeling approach across a variety of consolidation conditions and settings. This research offers a first approximation on the relative importance of social dimension driving consolidation within the context of informal development; research method use multiple working hypotheses and generalizations based on the review of four in-deep surveys, which where developed in consolidated settings of former informal areas in Lima at household scale.

Reviewed surveys provide information from secondary sources in the period between 2005 and 2014, which matches period for imagery data collection.

Insights from surveys and main findings could be summarized by the following items:

Table 5: Reviewed surveys on consolidation in Lima.

Author, Year, Country	Title, Type	Method used, Data source	Objective	Results	Conclusion
Williams S., 2005, USA	"Young town" growing up. Four decades later: self-help housing and upgrading lessons from a squatter neighborhood in Lima (Master Thesis)	Historical housing trajectory as the unit of analysis, household interview (31)	How low income families were able to upgrade their houses (factors that influence)	Self-help address immediate housing needs; tenure and loans have effect on decision	Need of more **dynamic** and long term method for evaluating development process
Tokeshi et al., 2005, Peru	Analysis tools for residential densification (Article in Spanish)	Field survey, physical features of houses, 80 neighborhoods	Typology of house consolidation	Characterization of actual condition, past process, future growth of individual units	**Contagion** of house typologies, block or neighborhood should be the planning scale
Peek O., 2014, Belgium	Living Between Desires and Possibilities: Revisiting and Re-envisioning the Self-Help House in the "Consolidated" Low-income Settlements of Lima, Peru (Article)	Longitudinal study at house level, intensive fieldwork session, ten households were documented using in-depth case studies	How consolidation process went on after more than thirty years of settlement, evaluate spatial and social changes in the neighborhood	In self-built environments "a home is forever". Outcomes show that comparable consolidation processes can result in very different built structures	Self-help house followed a model of a **single-family**
Tamura et al., 2014, Japan	Research on housing and urban improvement process for low income population. The case of self-help housing and urban self-management in Lima, Peru (Article)	Nine interviews of households, drawing house plans with the history of consolidation	Basic understanding of self-help housing	Where urban self-management was employed, "the neighbourhood was created through community's efforts"	"Further research require **monitoring** different cases of self-help and urban self-management that emerges spontaneously"

- In Williams (2005) it is stated the need of a more dynamic approach in explaining consolidation
- Tokeshi et al. (2005) found that there is contagion observed in similar formal house typologies that are copied between households
- Peek (2014) detect a typical single-family household growing-up across consolidation process
- Tamura et al. (2014) suggest that monitoring of the process is essential for understanding consolidation

5.3 Devising rules of state transition

A main assumption is that grouping spatial and individual physical variables influences house consolidation under informal development conditions. The tool used to explore non-centralized process of independent house development is the agent based model of households interactions into block scale. Moreover, as few houses are consolidated, a great amount of shelter is left in precarious state; therefore is important to provide information over housing creation mechanisms that are useful to streamline house development and improve living conditions. Described fact limits a quantitative based description of micro-scale urban growth. Physical state conditions of house are observed to be dynamic; thus, monitoring the change and elucidating the mechanism that produces it may provide information to better describe consolidation properties and link them to housing development policy prescription. An initial issue of handling this kind of micro-scale study, is that data should describe appropriately this fine grain scale, which addresses methodological challenges of object identification and description. Therefore, the methodological framework required to conduct this exploratory research should also allow both inclusion and operationalization of the concept of transition at house scale along time. Analysis starts at the representation of the different states of construction in the houses in the period of study (2002 to 2015). Data set of present housing structures is showing the status of both a individual house unit and the local neighbors that surrounds it; therefore two spatial entities are defined: the house and its environment. This focus is going to be used in the analysis as it is looking for relationships between households.

Proposed experiments measure social interactions and spatial processes use a single variable: construction state. Rules of state transition are acquired and stablished by identifying spatial patterns surrounding those houses that change its state; two maps at the scale of the block will serve for this purpose: first, maps that show types of state transition , and second, maps that show those houses that change and those that does not across the period. Using empirical data at scale of cities Bettencourt et al. (2007) found that as a general rule "growth is constrained by the availability of resources and their rates of consumption". In self-help building schema housing needs are meet once resources are available (Williams 2005); moreover, considering uncertain income distribution in urban poor population within the neighborhood, house upgrade occurs stochastically among those householders distributed in space of the block.

As social and spatial dimensions are considered basic elements in state transition, two different rules should be devised in order to provide a setting for comparison; the first, is a simple upgrading rule that drives change of state in the target house if the average state in adjacent houses is greater than it; second, block neighborhood adopts a structure of a social network, whose topology resembles house locations in the block, where change is driving by influence from those houses that have the greater state using an epidemic diffusion mechanism.

Described simulation experiments are aimed to compare different influence settings consisting of two socio-spatial influence frameworks within the lattice space of the model: Von Newmann neighborhood and Non-directed network. Settings for the models of influence resemble two different categories of proximity called adjacency and network to test effect on transition; these two categories of influence are passive and active respectively.

Passive rule correspond to a simple upgrading algorithm that selects randomly a given cell in the lattice and evaluates against its local neighborhood (Von Newmann), which is composed by adjacent cells; higher state cells have effect on transition. Here, target cell, wait passively to be randomly selected and then compared with its local neighborhood; if the average value of surrounding cells is higher than the target then the cell upgrades its state. On the other hand active rule is configured by network structure, where nodes occupy corresponding cell locations in the lattice and adopted its states conversely. An epidemic diffusion algorithm is adapted in this spatial and topological setting to provoke diffusion of change in state from an active group of nodes that have the highest state in the network. Number and locations of active actors are changing along the process; therefore, spread of upgrade decision is non-linear, even as the number of connections keep similar for all the nodes from the beginning of simulation. Using these two different settings, proposed investigation seeks to find evidence of influence effects on state transition as a result of two divergent mechanisms. In both cases the number of neighbors is three and are maintained fixed in order to make both social influence structures comparable. Simulation outcomes are time-series graphics and spatial configuration block lattices. Validation method applies to the later; this validation procedure is called Invariant-Variant method (Brown et al. 2005). Method is spatially explicit and evaluates not only model accuracy regarding right allocation of developed houses, but it also measures the likelihood of path-dependence along the process. Thus, selected validation method assesses both the spatial dimension and the non-linear nature of the process, where stochastic elements within algorithms incorporates a random component that come close to timing in independent upgrade decision-making.

Consolidation system is going to be replicated and operationalized via computer simulation of households decisions on specified physical environment; decisions by actors are already established through behavior rules; agent-environment relationship are incorporated in the rule and could be adjusted responding to heterogeneous conditions of block size, composition and configuration. Robinson (2007), suggest that analyzing land use change trajectories is useful to test hypothesis or scenarios about relationships between two elements of the system: 1) agent decisions and 2) a range of spatial and contextual variables; these relationships are parameterized accordingly in order to be included in the model; this author highlights the usefulness of GIS "to establish quantitative parameters to those relationships".

5.4 Models building

Consolidation models are designed as an explicit and dynamic analogy of house state transition, that includes spatial and social components; dynamics are achieved by using explicit rules that acknowledges direct influence of neighbor condition on the transition of state in a given house that perceive this state difference in either spatial (CA) or social settings (ABM); moreover, a important reason for having two models is to evaluate two types of spatial extent of influence: adjacent and separated neighbors. Therefore, consolidation systems as a complex system "must be modeled by taking into account the rules of interaction, the natures of the agents, and the way the agents, rules, and ultimately whole systems came about" (Adami 2012). These decision rules are derived from quantitative and qualitative representation of spatial features found in the data; basic model structure is composed by houses and interrelations between households who are the social entity that inhabits the house; these models are credited to be the appropriate for inference and explanation of the nature of state transition along the process of informal housing consolidation. Models summarizes an approach that seeks to preserve the meaning of the house consolidation process, as a sequence of states following a non-linear path-dependence trajectory.

Thus, model is built first through specifying actors, observed decisions, variables, parameters, and thresholds; then, designing the contextual space where agents interact each other is incorporated. Present investigation uses specific regular block layout that was already identified in the empirically retrieved sample, and transforms it into a lattice space or grid that is incorporated in the artificial space of the model. Basic assumption is that of the houses constantly monitoring state on their adjacent or connected neighbors, deciding to upgrade by looking at the changing state of surrounding houses. Therefore, agents behave according to an heuristic rule (Simon 1996) and during the different time-steps along consolidation as they are "embedded in the process and have a ostensible view of it" (Edmonds 2015). Thus, consolidation model becomes a formal model that is important because it is "unambiguous, that is it can be communicated many times without being distorted, and where different people will make the same inferences from the same model" (Edmonds 2015). The target of the model is to represent consolidation process, and to simulate the dynamic state transition process in order to investigate the emerging spatial and temporal outputs that come from the specific settings that are based on empirical data; the investigation follows the analytical sociology approach of Boero and Squazzoni (2005), who argue that "models need to be viewed as generative tools, because they allow formalizing a representation of the micro-macro mechanism responsible for social outcomes to be brought about"; and following with this logic and directions; designed models and related simulations look to make clear house consolidation process "by referring to a set of entities and processes (agents, action and interaction) that are spatially and temporally organized in such a way they regularly bring about the type of phenomenon the social scientist try to explain" Boero and Squazzoni (2005).

Clearly established and unchanging physical boundaries across the development process help to characterize the block, its layout influences internal socio-spatial structure and spatial and temporal outcomes. Spatial development and social interactions within the block are associated to the dynamic of house consolidation at block scale. As new emergent physical and social properties are created during simulation, they may address institutional dimensions in the trajectory towards formalization, which is related to the process of urban densification. Both the informal origin and individual consolidation of houses defines the nature of its change, which can be represented by measurable attributes of construction state; it is also argued that block dynamics are abundant of social interactions derived from spatial proximity that allow perceptions that key actors have on changes produced in its neighbors. Measurable attributes of objects at parcel scale are structural, infrastructural and demographic (Galster 2001); change in the attributes of an object located into the network of interactions affect decision to upgrade houses. Arranging this attributes and its dynamic trajectory towards explicit rules, allows to combine spatial and social dimensions, and to operationalize interactions and its effects at bottom level. Moreover, allocating dynamic behavior rules allow individual households to adapt to changing conditions and to generate emergent outcomes at upper scale, which can be tracked in the model and compared to actual spatial patterns. In complex systems, rules that govern behavior at bottom scales leads to the emergence of changing state configurations at upper scales that are the result of individuals' adaptation to its surrounding conditions. Internal rules that drives behavior of individual units at a given scale are similar to the rules driving evolution in the natural realm. Individuals adapt to internal state conditions and to external institutions; therefore, dimension of interactions emerge at consolidation space.

Finally, to operationalize prediction-aimed simulation, Simon (1996) recommend that "data about the future predictions are commonly the weakest points in our armor of fact. Good predictions have two requisites that are often hard to come by. First they require either a theoretical understanding of the phenomena to be predicted, as a basis for the prediction model, or phenomena that are sufficiently regular that they can simply be extrapolated. the second requisite for prediction is having reliable data about the initial conditions, the starting point from which the extrapolation is to be made".

"Agent-based models can explicitly formalize simple to complex representations of the behavior and cognitive processes of actors who make land and resource use decisions within the system" (Robinson et al. 2007). "Perhaps the greatest attraction of a cellular automata based approach for the spatial sciences is the equal weight given to the importance of space, time and system attributes" (Batten 2001). The space of maneuver of these actors is located into a micro scale network of relationships and its related and explicit spatial context; interactions and influence comes by both the same level and the superior scales sets of allowances and constraints. Thus, the problem is to find from empirical data) heterogeneous, representative, and proportional groups of actors (and states) to represent those that intervene in the actual system; to make this selection it is important to take into account "the scope and scale of analysis, as well as the degree of heterogeneity one wishes to capture" (Robinson et al. 2007).

Robinson et al. (2007) stated a basic requirement for ABM: to be "credible and defensible representations of micro-processes"; and also remarked a major need for this case: the problem is to find an apparent theoretical approach for capturing micro processes from empirical data. Thus, suggested aim is to investigate real world consolidation and improve current theories; then, under the conditions and scope of above-mentioned evidence and rationale identified during this investigation, a more specific problem arises that is to develop a procedure able enough to identify, understand and test decision-making drivers of consolidation and choose the case-relevant ones, in order to test its relevance both in theory and practice. Robinson et al. (2007) suggested a method to develop computational instruments from empirical data; this method is called Field and Laboratory Experiments (FLE). It is argued that this method is suitable for the task of testing but not creating theories; however, information produced by using FLE method is useful in calibrating decision-making algorithms to the empirical data available; thus, its rationale is similar to that used in developing econometric models. Following this method, it is recommended to use GIS and remotely sensed data first to determine agent decisions and its rules and also to include space settings in the model; GIS is stated useful in cases where actual theories of decision-making selected rely on spatial accessibility (streets network) and biophysical suitability (Robinson et al. 2007).

The method devised for this investigation on consolidation, ensemble these approaches and suggestions and devise rules from both empirical data obtained from satellite imagery and secondary sources from household-level surveys on house consolidation in Lima.

5.5 Validation approach

"Many simulation models just model stylized facts, and as such they are interesting and often helpful. But simulation models can be seen as an implementation of theory in a computer, and this is why at least an empirical validation should be aimed at" (Troitzsch 2015). "Validation assesses the degree of correlation between the model output and the conceptual framework of the model" (Roy et al. 2014). Validation involves assessing the success of a model or simulation run in achieving its (specific) intended goals; comparing the performance of the model to some properties of the real system being simulated (Torrens 2002). Troitzsch (2015) recommends that "if a simulation model is to be validated in a concrete empirical setting, it should be initialized with empirical data in order that one can test whether the model behaves the same way as the target system". Validation will be performed to make it possible to evaluate the general hypothesis of neighbors influence in house upgrading including the access component. As it has been explained in both replication protocols (ODD and ODD+D), initial settings of the simulation are equal to those observed in real world. "Validation involves assessing the success of a model or simulation run in achieving its (specific) intended goals, comparing the performance of the model to some properties of the real system being simulated" (Torrens 2002). The model has been built with the purpose of replicate the spatial and temporal dimensions of state transition in the space of the block. The type of validation that is going to be used is the so called replicative validity, where the model matches data already acquired from the real system (Zeigler 1976).

Current research adopt and test the two distinct notions of accuracy in land use models mentioned by Brown et al. (2005):

- Predictive accuracy, where the predicted spatial pattern can be highly correlated to the actual configuration;
- Process accuracy, where the process by which locations or land use patterns are determined can be consistent with real world processes.

Kocabas and Dragicevic (2006) argue that this approach represents a calibration procedure since the model and simulation outputs are compared with the actual data. Validation is performed comparing both changing composition along state transition trajectories (Process accuracy) and final spatial configuration (Predictive accuracy). Regarding predictive accuracy, Invariant-Variant method (Brown et al. 2005) is used. Validation depends on the objective of the model; in this sense accurate predictions are not the unique goal, rather the objective is "to reproduce critical systems properties in terms of spatial and temporal dynamics" (Barros 2012). "To investigate the errors associated with individual classes, multinomial tests must be used, these answer the question of 'what is the nature of the errors: which classes or properties are not mapped correctly?'" (Rossiter 2014). Validation is performed as multinomial test because the aim is to evaluate the degree of matching between actual and simulated values of each of the four categories or house states; this method use the confusion matrix or matrix of contingency, that is a table with columns representing the actual or reference classes and rows the resultant simulated classes. "Many of the quantitative methods for the calculus of simulation accuracy involve the construction of a contingency matrix from the two sets of data. A matrix of contingency is an effective way of representing map accuracy and the accuracy of each and every class individually described by the inclusion errors (commission errors) and by the exclusion errors (errors of omission) present in the classification" (Couto 2003). During validation as well as in the model settings it is assumed that each cell should correspond to only one house. Along with this fact it is necessary to remark that cell-by-cell or pixel-to-pixel matching is a very exigent test for validation because "it is extremely difficult to simulate and predict the precise location of urban lands due to the complexity of the urban system" (Al-Ahmadi et al. 2013). In both the observed empirical spatial data, and the constructed dynamic framework consolidation system the particular characteristics of block size and number of classes make it matching more dependent on randomness than on the specific transition rules.

A specific limitation on using both Kappa indicators and Confusion Matrix for real datasets in cities is expressed by Kocabas and Dragicevic (2006) who argue that this indicator does "not quantify the patterns or map classes that represent geographic features, thereby making even a small difference of land uses types between two maps to be shown as an inconsistency"; they also use the Kappa index as one measure to analyze the degree of similarity between outputs when varying different CA element configurations. In this sense also Wang et al. (2012) assert some hesitation in applying those measures: "the validity of the model results have been evaluated by comparing the Kappa index of agreement for each category, spatial patterns of land use type and fractal parameter. Kappa index can give a summary of static agreement in terms of the proportion of the total number of pixels, but it is too simple to express the spatial patterns and spatial distribution". Acknowledging this limitation a prior quantification of error will be useful to test the validity of the results in the spatial dimension, given the particular characteristics of both the real wold and the model that aims to replicate it. Two important characteristics that will also influence the validation indicators are the small size of the cellular space or lattice that depict the block, and the number of categories that represent the construction states. To make it possible a more comprehensive account of the degree of predictability and the progressive changes that are happening in the model, the Invariant-Variant Method (Brown et al. 2005) is adopted as a second reference to measure the degree of predictability that the model achieves.

6 Results

6.1 Empirical data acquisition

Tokeshi et al. (2005) proposed a classification scheme to characterize construction states during consolidation for houses that are built via self-help construction, which are located in Lima metropolitan area. Four categories of house consolidation have been established in order to characterize construction states for Visual Identification and further modeling. These four categories are coded and described as follows, it is noticeable that physical transition from non-finished to finished house structure is fixed from B to C; thus, the following categories are considered when mapping:

(A) Vacant lot or provisional shelter structure made of precarious material (Non-finished house);

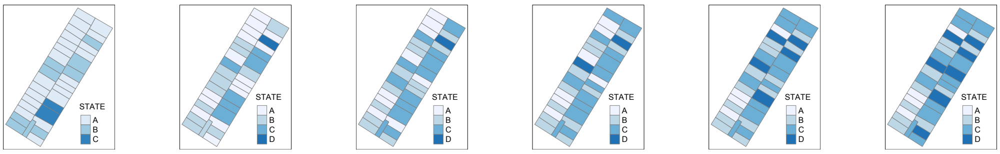
(B) Improved shelter structure made of bricks and concrete walls with corrugated sheet roofing (Non-finished house);

(C) Permanent structure of one story made of brick and concrete walls with light concrete roofing (Finished house);

(D) Two or more stories house with light concert roofing (Finished house);

Blocks have been selected trough visual identification of high-resolution imagery retrieved in 2002, 2006, 2009, 2011, 2013 and 2015 from Google Earth; selection criteria requires the blocks not only to be present at 2002 but also to be clearly delimited showing houses at the consolidation states according to explained categorization. Sample is composed by three parcels (which are identified as parcels 1, 2, and 6) and their internal blocks (which are identified using letters following the number of the parcel they belong to, e.g. Block 1a). Sub-numbering is used to make it possible to identify blocks that belong the same parcel; number of sampled blocks sums 13 in total. Sampling methodology was performed using already described hierarchical spatial structure composed by parcels, blocks and houses. Sampled blocks vary on number of houses and on composition and configuration of states. This heterogeneity allows to keep variety in the sample, and compel us to seek a general rule that could replicate each condition. From this initial dataset, six blocks that have only residential use are further selected in order to be used for calibration and validation; it is important to remark that the two conceptual models are intended to be general models of residential house consolidation; therefore they can be able to replicate any block consolidation condition observed in real world under the characteristics of regular block layout and identifiable consolidation stages.

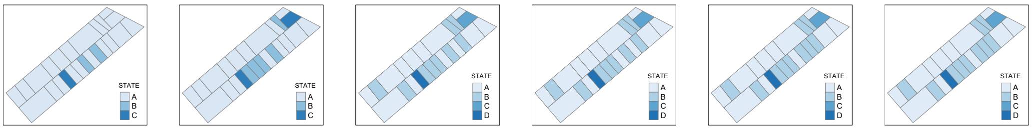
To make it possible to systematize the visual identification procedure and to provide a method for replication, a Visual Identification Protocol have been developed and formalized; protocol has two consecutive parts: the first is for house or lot detection and digitalization into a GIS format, and the second is for state categorization (Figure 22). This Protocol employ both the common visual identification standards for built units such as shape, color, texture, etc. and the specific features the four different housing



(a) 2002 (b) 2006 (c) 2009 (d) 2011 (e) 2013 (f) 2015

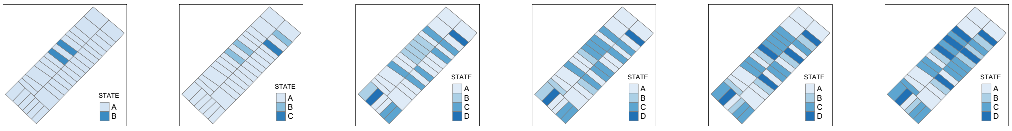
Figure 24: Choropleth maps of state Block 1a

categories have, for example: soil, roofing material, and extension of shades. A final detection of lot and house number is performed using Street View photos taken in year 2013.



(a) 2002 (b) 2006 (c) 2009 (d) 2011 (e) 2013 (f) 2015

Figure 25: Choropleth maps of state Block 2a



(a) 2002 (b) 2006 (c) 2009 (d) 2011 (e) 2013 (f) 2015

Figure 26: Consolidation maps of state Block 6a

6.1.1 House consolidation maps

Spatial data base created into a GIS environment have provided the basic representation of rectangular housing blocks as basic urban elements surrounded by streets (Figures 24, 25, and 26). These blocks are subdivided into lots, which in turn may be occupied by the structure of a single-family house, which resembles features of high density residential houses according to Peruvian Construction Code (2006). The spatially referenced map show blocks and houses boundaries along with the state attributes of houses. From the later dataset another graphic is built with the aim of provide state composition and configuration, which permits to calculate the percentage of occupation each class have along the six established years. Resulting graphs present quantifiable trajectories of increasing or decreasing presence of each class which indicate actual trends of house development (Figure 27).

For instance for the case of Block 1a, the percentage A class into the selected blocks ranges form 79% to 100% in 2002, and declines steady in all blocks registering a com-

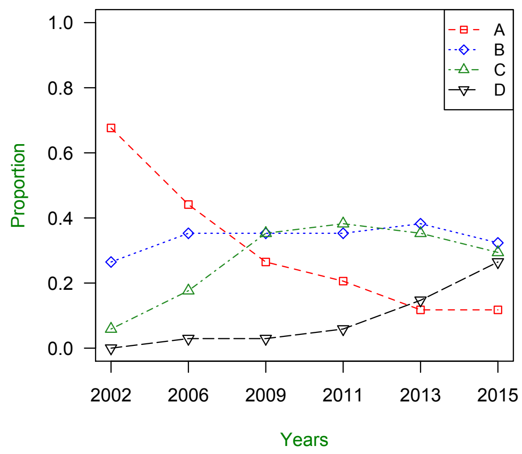
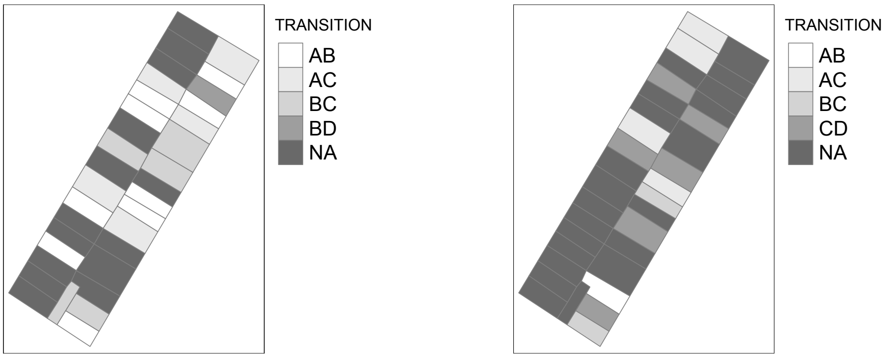


Figure 27: Trajectories of consolidation states in Block 1a

position that ranges from 15% to 35% in 2015. Therefore this information provides particular knowledge of consolidation class A related to the amount of occupation, the declining trend and the relative proportion as registered in 2015; also it can be inferred that because class A is already present, consolidation process is not finished yet, and the urbanization is still at a midway towards finishing. B class percentages in selected blocks show a clear increasing trend but this growth is not fast but rather it is slow and by 2015 it does not surpasses the 40% and presents some stagnation or flattening; this pattern may explain the transition nature of this type of house that once appeared may easily be converted to C class by improving roof material. Following the previous explanation C class also shares the same transition nature of B class, and this is proved by observing the parallel trajectories they have; C class values range from 0% to 40%. Finally D class appeared in a range between 5% to 30% of the total composition present in the blocks; this range confirms that consolidation is still progressing and time ahead is at least of the same length of the already elapsed 14 years period starting in 2002.

6.1.2 Transition and variation maps

Changes in the state of construction on individual houses are identified within housing blocks; spatial representation is done via distribution maps; these categorical maps of transition types shows state transition at the scale of houses in six selected years: 2002, 2006, 2009, 2011, 2013 and 2015. Transition process can be tracked through the maps and specific features of this progression can be identified. These spatial data is used to generate ideas in a exploratory way, investigating how the latest states are related to previous conditions (Byrne 1998); last statement refers to the concept of path dependance that is characteristic in complex systems.



(a) 2002 - 2009 (b) 2009 - 2015

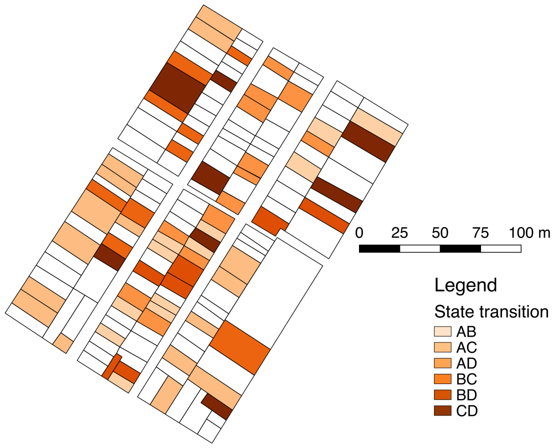
Figure 28: Transition maps Block 1a

Along the studied period from 2002 to 2015, transition phases are observed in five consecutive stages: 2002 to 2006, 2006 to 2009, 2009 to 2011, 2011 to 2013 and 2013 to 2015. Moreover at each stage five types of transition have been identified: A to B, A to C, B to C, B to D, C to D. Of those transition types the two most frequent are A to B and B to C, with 12 and 10 transitions out of the total of 37 recorded transitions; results also show that from 2009 the total number of transitions decreases. These empirical information (Figure 28 and 29) is translated to parameters and rules that feed the model framework; the overall scope looks on identifying transition process at house scale, feeding empirical based simulations, and summarizing results at block scale. The study of transition process involve a systematic approach to represent the block, houses and interactions among them along the time; therefore the process is analyzed through detection of relevant house states and its temporal dynamic; synthesis is performed when simulating the process and observing emergent properties of spatial nature as path-dependance, which can describe underlying complexity.

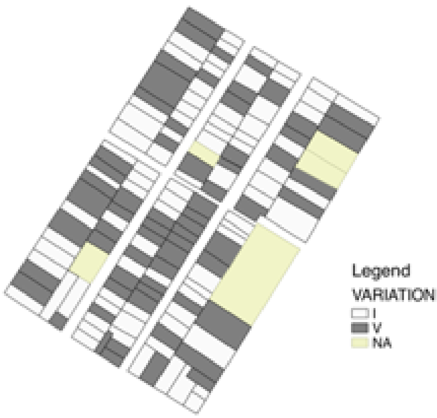
6.1.3 Spatio-temporal patterns

A study comprising blocks and its neighbors located into the same parcel aims to provide data on patterns present at the same place considering the fact that all blocks started housing development at the same time when the whole parcel was subdivided. For example the six blocks belonging the Parcel 1 have all similar trends observed in previous studied blocks, that can be summarized as a sharp decrease in A class, and a significant presence of class B at the beginning and even at the finish of studied period (2002 to 2015); the proportion of B class duplicates that of C and D classes together; described condition raises three questions:

- when transition will occur in B class houses?
- what is the spatial pattern at the moment of this transition?



(a) Transition



(b) Variation

Figure 29: Transition and Variation maps of Parcel 1 (2002 - 2009)

- does spatial composition and configuration drives upgrade?
- more specifically, does neighbors state influence upgrade in particular house?

Last two questions are used to devise a rule that can simulate upgrading process. As the objective of these data-driven spatial analysis is to inform algorithm building, devised rules are required to specify the system sufficiently y replicating spatial and temporal configuration of state transition emergent at block scale; simplifications and tradeoffs are to be made in selecting a particular variables and parameters to set off algorithms for application in representing consolidation; main restriction here is the lack of information at individual level, that match the bottom level approach to study consolidation. The

Table 6: Transition types in blocks belonging Parcel 1: 2002 to 2009

Transition type	Blocks 1a	1b	1c	1d	1e	1h	Total
AB	9	8	2	7	3	6	35
AC	5	3	5	0	1	1	15
AD	0	0	2	1	0	0	3
BC	5	0	0	0	2	0	7
BD	1	1	0	0	0	1	2
CD	0	0	0	0	2	0	2
Total	20	12	9	8	8	8	64
Block size	34	26	24	23	20	24	-
%	59	46	38	35	40	33	-

Table 7: Transition types in blocks belonging Parcel 1: 2009 to 2015

Transition type	Blocks 1a	1b	1c	1d	1e	1h	Total
AB	1	2	3	2	0	3	11
AC	4	1	2	0	0	1	8
AD	0	0	1	0	1	0	2
BC	2	1	0	3	2	0	8
BD	0	0	0	0	0	1	1
CD	6	1	2	0	1	0	10
Total	13	5	8	5	4	5	40
Block size	34	26	24	23	20	24	-
%	38	19	33	22	20	21	-

Table 8: Transition types in blocks belonging Parcel 2: 2002 to 2009

Transition type	Blocks 6a	6b	6c	Total
AB	3	0	3	6
AC	8	4	2	14
AD	2	1	2	5
BC	0	0	0	0
BD	0	0	0	0
CD	0	0	0	0
Total	13	5	7	25
Block size	35	16	27	-
%	37	31	26	-

Table 9: Transition types in blocks belonging Parcel 2: 2009 to 2015

Transition type	Blocks 6a	6b	6c	Total
AB	5	0	1	6
AC	4	0	2	6
AD	0	2	3	5
BC	3	0	0	3
BD	2	0	1	3
CD	3	4	2	9
Total	17	6	9	32
Block size	35	16	27	-
%	49	38	33	-

analysis of the neighborhood should allow to define some transition rules that could be applied on target cells to upgrade sequentially.

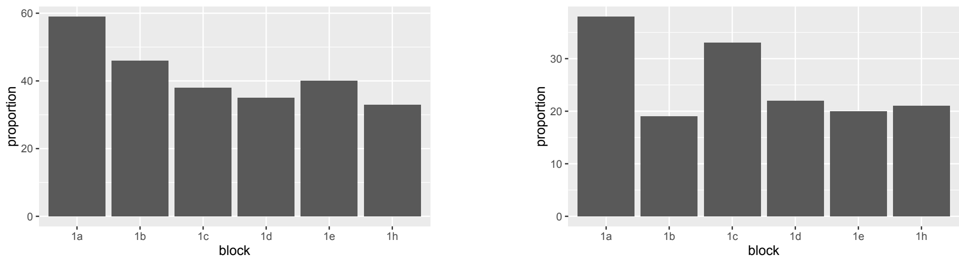
Observing transition and variation maps (Figure 20), as a general rule and focusing only in those houses that have upgraded in the reference periods 2002 - 2009 and 2009 to 2015, it could be noticed that in those neighbors adjacent to upgraded house in the previous step before upgrading, they had either similar or upper states than upgraded house, or were in greater states than A at 2002. Regarding spatial agglomeration, in Block 9 it was observed that 82% (40 units) of upgraded houses (in 2002-2009) and 86% (49 units) of upgraded houses (in 2009-2015) are adjacent and form clusters. In Parcel 2, there is a small rate of transition in the 46 houses of Parcel 2; first period (2002 - 2009) has the smallest rate with only 9 houses changing states, compared to 15 houses in the second period, which is still small compared to other parcels. in both period there is stagnation in the transition of poor houses to upper states, the number of poor houses (states A and B) keeping its states are 37 and 27 in periods 1 and 2 respectively; meanwhile the second period accounts for the largest amount of houses transitioning

Table 10: Transition types in blocks belonging Parcel 6: 2006 to 2009

Transition type	9a	9b	9c	9d	9e	9f	Total
	Blocks						
AB	2	6	4	5	3	1	21
AC	8	0	1	4	1	1	15
AD	0	0	1	0	1	3	5
BC	2	4	1	2	1	2	12
BD	0	0	1	1	0	1	3
CD	1	0	0	0	2	0	3
Total	13	10	8	12	8	8	59
Block size	31	25	11	30	21	19	-
%	42	40	73	40	38	42	-

Table 11: Transition types in blocks belonging Parcel 6: 2009 to 2015

Transition type	9a	9b	9c	9d	9e	9f	Total
	Blocks						
AB	2	0	1	1	0	0	4
AC	0	3	1	2	1	0	7
AD	1	0	0	1	1	4	7
BC	1	3	1	3	0	0	8
BD	2	1	0	0	2	0	5
CD	7	3	0	7	4	3	24
Total	13	10	3	14	8	7	55
Block size	31	25	11	30	21	19	-
%	42	40	27	47	38	36	-



(a) 2002 to 2009

(b) 2009 to 2015

Figure 30: Proportion of houses in transition in blocks belonging Parcel 1

from poor to rich status (9 houses). These findings provide following four characteristics of state transition process:

- all non-consolidated houses that upgraded its state were surrounded by houses with similar or greater states,
- upgraded houses of consolidated and non-consolidated states form aggregated clusters of same state,
- initial state configurations have effect in the final configuration,
- upgraded houses at each period are allocated randomly.

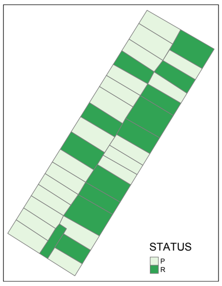
6.1.4 Socio-economic insights

Spatial composition and configuration at block scale provides information on the distribution of the physical conditions present at this basic level of the urban fabric. Moreover those distributed physical states and attributes may provide indirect measure of socio-economic conditions of households. A possibility to link individual state attributes together emerges as a real possibility oriented to further explore the existence of interaction due to proximity, and explicit rules that drives house consolidation. The absence of explicit socio-economic data in the distribution maps, require to devise a modeling-based method which should be validated prior application. Thus the working hypothesis states that construction state measures can be used as predictors of house consolidation at block scale, using state variables as proxy for socio-economic conditions. Once state transition patterns for each four classes of consolidation is performed, both rules can be defined more precisely and outcomes can be analyzed from a synthetic view. Therefore the concept of Socio-Economic status is employed to replicate consolidation and generate information on dynamics of consolidation process.

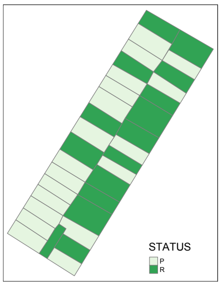
Modeled blocks are aggregations of houses configuring spatial grids composed by cells that are representing actual houses having particular states; these states in cells are assigned employing actual state configuration in the six selected blocks in year 2002. Initial heterogeneous state conditions have effect on the potential of a given block to reach development. Another parameters are the block dimension or the number of cells composing the block, and the number of neighbors that are considered influencing upgrade. There is no absolute concept of time periods like months or years as the model runs over time steps; thus the number of time-steps required to get block consolidation depends on two initial parameters: number of initial consolidated houses, and block size (number of houses).

As it has been mentioned parametrization refers to such characteristics of the system that influences upgrading, and plays an important role in how the development rule drives agent performance. The rule is simple: detect and follow those houses in better condition; complexity arises as rules are applied into a heterogeneous environment and thus the key point is to track the different settings and its influences and identify those spatial configurations of house state that make both individual houses and entire block to develop. The general operation of the modeled system at block scale resembles that observed in house consolidation at block scale that is first characterized as a long term process where individual houses are upgrading independently its construction state (Tokeshi et al. 2005, Barros 2012). Along consolidation neither formal ownership nor public utilities are credited to having major influence in development compared to individual housing needs (Williams 2005). Progression of development by following the trajectory of spatial configuration of states in the houses into fixed block boundaries can be replicated by the operation of rules and also can be tracked along time steps. In order to implement the rules a formal algorithm should be envisaged, it addresses the mechanism of state-based interrelations and provokes spatial order to emerge from individual interactions. Used parameters are those identified in the context of informal development in Chillon valley.

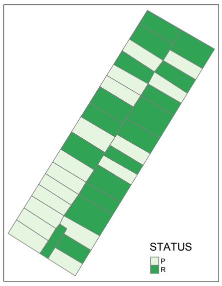
Actual representation as well as the model and simulation of the consolidation process are presented quantitatively.



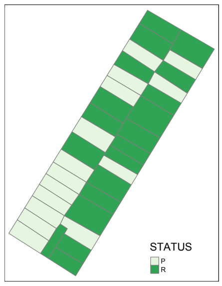
(a) 2009



(b) 2011

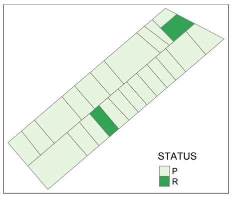


(c) 2013

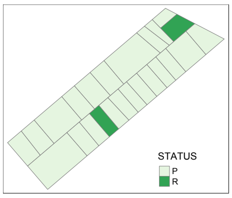


(d) 2015

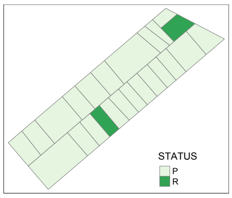
Figure 31: Binary maps for block 1a



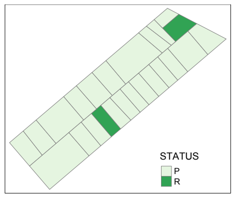
(a) 2009



(b) 2011

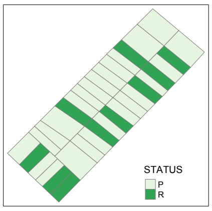


(c) 2013

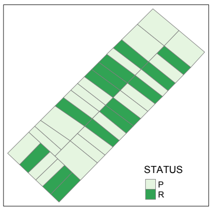


(d) 2015

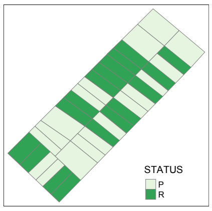
Figure 32: Binary maps for block 2a



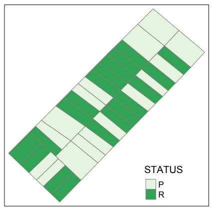
(a) 2009



(b) 2011



(c) 2013

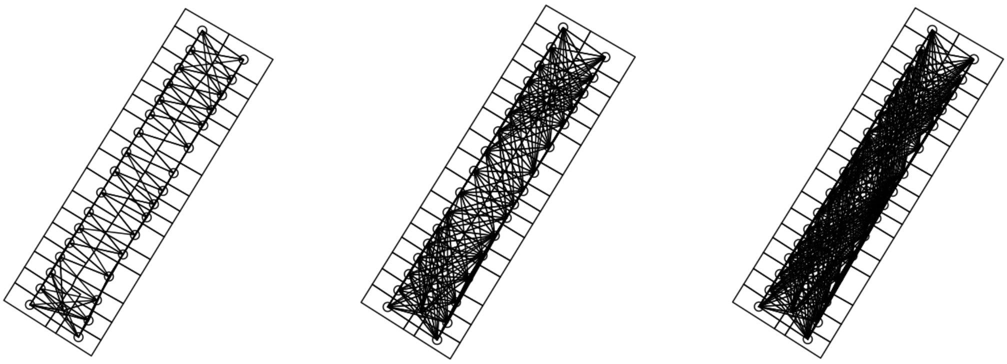


(d) 2015

Figure 33: Binary maps for block 6a

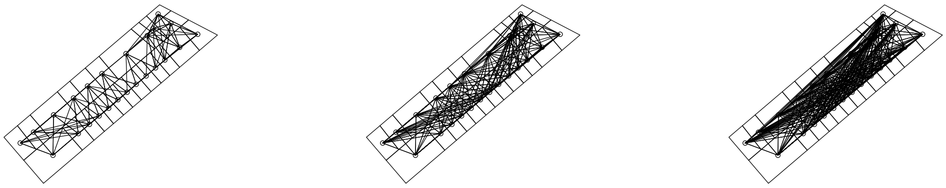
6.2 Spatial dependence analysis

Spatial dependence is analyzed using spatial autocorrelation method; data input comes from already mapped spatial composition and configuration data at block scale; the aim is to test if spatial clustering exist in finished houses along the process of consolidation. Join Count statistics (Cliff and Ord 1981) is the specific method used to measure spatial autocorrelation and determine if house construction state is spatially dependent on the state of neighboring houses. Autocorrelation measurement is applied at block scale, which is the urban spatial unit where houses are located in a arrangement that follows typical configuration of residential blocks regulated by Construction Code and present in Lima Metropolitan Region. Spatial Autocorrelation makes possible to characterize and evaluate the spatial distribution of finished houses: grouped, random or dispersed.



(a) k7 (b) k14 (c) k21

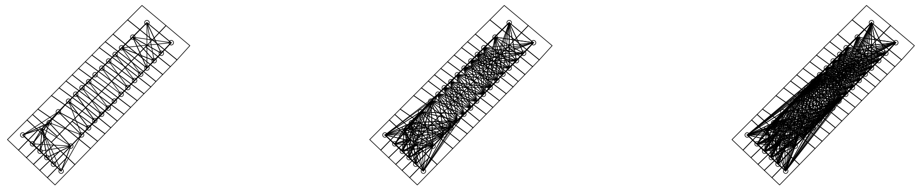
Figure 34: Three numbers of neighbors (k) for block 1a



(a) k7 (b) k14 (c) k21

Figure 35: Three numbers of neighbors (k) for block 2a

Autocorrelation is analyzed at block scale and considering three different numbers of neighbors (seven, fourteen, and twenty one). The study considers only two categories: finished and non-finished houses; the first category comprises C and D state classes, while A and B includes the later category of non-finished houses. Analysis start in 2009 because is at this year where the number of units belonging the finished category begin to appear and starts a noticeable increasing; described fact allows to have enough data (constructed units) to apply the method. Finished and Non-finished status are represented by a binary pair (1 and 0 respectively), because of the implicit socio-economic nature of this categorization these two classes are also called Rich and Poor; houses are represented as an area in the spatial data base, the aggravation of these areas configures a spatially referenced block. Resulting binary map is a choropleth map that shows the spatial distribution of two categories (Figures 31, 32, and 33). Join Count is the method to measure the number of joins or adjacencies between areas of a particular type accordingly to the data presented in the binary mapImplementation aims to test if the observed spatial pattern is produced by a random-allocation process in which houses are



(a) k7 (b) k14 (c) k21

Figure 36: Three numbers of neighbors (k) for block 6a

	Actual values for 1:1		
	k=7	k=14	k=21
2009	2.14286	2.464286	2.380952
2011	3.00000	3.285714	3.261905
2013	4.07143	4.392857	4.333333
2015	5.14286	5.321429	5.404762

	Expected values for 1:1		
	k=7	k=14	k=21
2009	2.36364	2.363636	2.363636
2011	3.18182	3.181818	3.181818
2013	4.12121	4.121212	4.1212121
2015	5.18182	5.181818	5.181818

Figure 37: Actual and expected values for block 1a

independently developed without considering states in nearest neighbors; described case configures the null hypothesis, which states that the process of consolidation at block scale exhibits no significant spatial autocorrelation. This global autocorrelation measure is applied at block level where individual houses are grouped, following a classic urban fabric pattern of Lima Metropolitan Region. This method makes possible to characterize the spatial distribution of houses: grouped, random or dispersed.

- "Grouped", the spatial dependency is strong positively because the contiguity of zones with the property "occurring" is significant and consequently important too for zones of "absence";
- "Random"; the spatial dependency is weak or even null because there is no similarity between the property of a zone and that of its neighbors;
- "Dispersed"; the spatial dependency is strongly negative because the adjacency of the zones where the property occurs with that of the zones where if is absent is significant;

There are three different possibilities of joins or adjacencies in the binary map:

- 0:0, undeveloped-undeveloped
- 1:1, developed-developed
- 1:0, developed-undeveloped

	z-values for 1:1		
	k=7	k=14	k=21
2009	-0.6456	0.4265	0.0739
2011	-0.5006	0.3999	0.2934
2013	-0.1327	0.9738	0.6876
2015	-0.1032	0.4764	0.6564

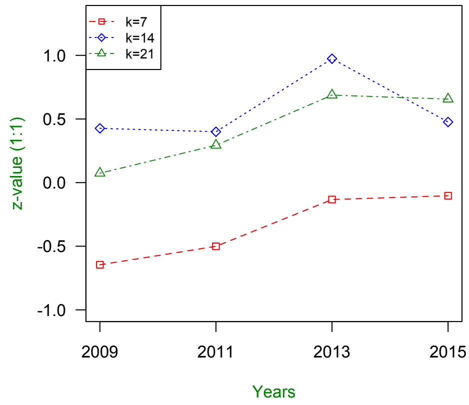


Figure 38: z-values for block 1a

	Actual values for 1:1		
	k=7	k=14	k=21
2009	0.0000000	0.0000000	0.047619
2011	0.0000000	0.0000000	0.047619
2013	0.0000000	0.0000000	0.047619
2015	0.0000000	0.0000000	0.047619

	Expected values for 1:1		
	k=7	k=14	k=21
2009	0.0434783	0.043478	0.043478
2011	0.0434783	0.043478	0.043478
2013	0.0434783	0.043478	0.043478
2015	0.0434783	0.043478	0.043478

Figure 39: Actual and expected values for block 2a

Using probability theory the expected number of joins per each type are predicted; actual number of joins are counted from the data; a particular parameter called z-value (or z-score) is calculated as follows:

$$z - value = (A - E)/SD$$

- A: actual join count
- E: expected join count
- SD: standard deviation of expected join count

Z-value is the probability of any one specified number of joins of a particular type is present; it is utilized to confirm if there is autocorrelation, according to the following rule: spatial dependence exists if the difference of the two values (actual and expected number of adjacencies) is very large, and the z-value is greater than the selected significance value (e.g. +/- 1.96, at 95% of confidence level). This test is used to characterize and test random allocation of development. Spatial analysis oriented to test spatial autocorrelation was performed using binary maps representing states in three blocks

	z-values for 1:1		
	k=7	k=14	k=21
2009	-0.7016	-1.4197	0.4185
2011	-0.7016	-1.4197	0.4185
2013	-0.7016	-1.4197	0.4185
2015	-0.7016	-1.4197	0.4185

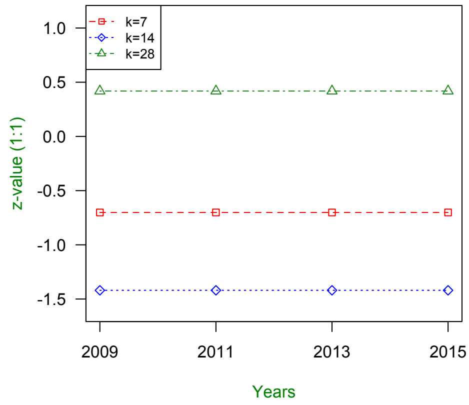


Figure 40: z-values for block 2a

	Actual values for 1:1		
	k=7	k=14	k=21
2009	1.142857	1.142857	1.119048
2011	2.42857	2.750000	2.809524
2013	3.71429	4.035714	4.190476
2015	4.71429	5.214286	5.309524

	Expected values for 1:1		
	k=7	k=14	k=21
2009	1.323529	1.323529	1.323529
2011	2.67647	2.676471	2.676471
2013	4.00000	4.000000	4.000000
2015	5.02941	5.029412	5.029412

Figure 41: Actual and expected values for block 6a

(1a, 2a, and 6a) in four years: 2009, 2011, 2013 and 2015; at each block adjacencies were calculated considering three number of neighbors (k): 7, 14 and 21; finally, the considered adjacency type is finished to finished (1:1).

6.2.1 Join Count statistics

Results show two main but different trends in z-values along time: the first case that considers Block 1 and Block 6, its values have an increasing trajectory, while in the Block 2 they maintain constant. In the later z-values are keeping the same value because during the considered period the number of finished houses does not increase. The only decreasing trend is present in Block 6 and correspond to the values belonging the least number of neighbors (k=7). At a given year all the sets of z-values show a noticeable increasing in the values as the number of neighbors increases; in the same way the gap or difference between actual and expected values of Join Counts in blocks 1 and 6 extends as the number of neighbors raises. In the specific case of Block 2, where the number of finished houses is scarce, the Join Count values are calculated only when the number of neighbors reach k=21. Values of Join Count graphics and z-values (1:1) in informal types, present similar trends in all cases except in Block 2, which can be considered an outlier

	z-values for 1:1		
	k=7	k=14	k=21
2009	-0.6242	-0.9181	-1.1735
2011	-0.7024	0.2836	0.5204
2013	-0.7569	0.1207	0.6117
2015	-0.8232	0.5880	0.8146

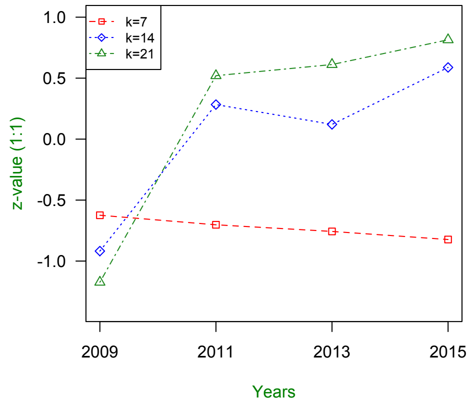


Figure 42: z-values for block 6a

in the analysis; it is explained because in Block 2 the number of developed houses is the same across the years from 2009 to 2015. The increase in absolute values of both Actual and Expected values of Join Count statistics are directly influenced by the increase of finished houses along the time; and because as a result of this densification process z-values also increases. However mentioned increase is performed without noticing spatial dependence in the indicators; in other words binary map patterns at the considered period and number of neighbors does show values that confirm null hypothesis of not spatial dependence. Calculated values in the two indicators suggest that blocks are still at early stage of development, and because of it it is expected that the number of finished houses will increase in the next years causing finished houses to become closer. Thus at later stages of development these used indicators will represent spatial autocorrelation caused by an infill process into fixed block boundaries rather than a spatial dependence process where upgraded houses will be occurring "naturally" as a consequence of the improvement of socio-economic conditions in the whole parcel or neighborhood. In general, the presented Joint Count indicators have been useful to characterize spatial process of occupation and differences between the specific block trajectories. Absence of spatial autocorrelation means that occupation and finishing are linked directly to individuals acting randomly, who do not observe other's condition to make their decision to develop. Spatial autocorrelation analysis is not sufficiently strong to suggest a dependence in the attribute of house development. It may be due to the particular nature of informal development within former agricultural parcels; these are former agricultural units with clearly defined boundaries that are developed independently regarding economic conditions of owners. Further analysis of these non-linear processes is likely to be oriented towards more dynamic approaches like those proposed by complexity theory; proposed approach considers to perform analysis using either cellular automata and agent based models. The aim is to link these processes to spatial interaction that may provide explanation on the subjacent dynamic mechanism of random allocation of states.

6.3 Conceptual models of house consolidation

House state is a socio-economic indicator that allows an exploratory analysis; sampling is performed identifying physically manifest socio-economic structures through progressive observation and identification at parcel, block and house levels. At the bottom level are the houses, which are the basic units of city structure and are treated as independent development units. Also house is considered a proxy of income to make it possible to determine household status. The typology of consolidation states is taken from Tokeshi et al. (2005) who studied the self-building process in Lima. Data gathering is performed using visual identification of high-resolution satellite imagery. Remotely-sensed imagery is used to extract construction features and classify the houses according to its states; a visual identification protocol is allows to make this step replicable. Classification maps of house states will also be used as a reference data for model calibration and validation. The analysis correspond to a longitudinal research that involves the houses as single subjects whose state is measured repeatedly each time-step over a defined period of consolidation that replicates the actual timeline from 2002 to 2015. Cowen (1998) argued that a research method have to recognizes the object of study and interpret the physical characteristics of the dwelling. A type of individual-based computational model called Cellular Automata (CA) admit explicitly the spatial and temporal nature of different types of houses and its local relationships into the space of the block. Physical and spatial data from housing structures present in the block are organized and analyzed through spatial autocorrelation in order to characterize the actual process of consolidation. Autocorrelation results showed no spatial dependence along the process; this empirical based finding suggest that a random allocation rule of states should be considered in the model. The consolidation model as a cellular automata machine is designed to explore state transition process along space and time for the specific case of informal development at the scale of the house, in the same way as Samat (2005) describe it: a "model with fine spatial scale datasets". CA consolidation model represents hypothesized factor that is credited to be driving the process: social influence through interactions between block neighbors. The resultant algorithm incorporates the observed spatial-based random nature of house state allocation. The study of interaction is rooted in the concept of Social Influence and Opinion Convergence as expressed by Festinger (1954), Degroot (1974) and Axelrod (1997); the focus of these theories is on the mechanism that social groups exert on shaping the individual opinion converging towards an average at the end of the process. Interactions are performed between households, the rule states the upgrading of states in houses is driven by the number of surrounding houses that are finished; thus working hypothesis express that household decision to upgrade its house state is influenced by observing the average condition of other houses in the block. This study suggest that informal urban growth is based on individual interactions that builds mixed spatial patterns at block scale; independent and decentralized informal development context makes the process to be complex. Within this complexity it is important to remark path-dependence mechanism along the way towards total development; If individuals value the characteristics of their neighbors, then (as an outcome of their choice of location), their neighbors characteristics are correlated with their own (Ioannides 2010). It is also possible that already developed houses have key role in influencing upgrading of other houses; Galster (2001) observes that key actors influences the flows of resources driving development, he states that the stock of attributes constituting neighborhood at any point are produced by flows of resources and these flows will be governed by perceptions of key actors. Thus, model considered here is a computational description of interactions that leads one house to upgrade its physical state; as the process of state transition is not analytically tractable it is considered to be dependent on the composition and configuration of houses into a clearly and spatially delimited block.

The models replicates the particular space of a informal block, at this fine grain each cell correspond to a single house, and these houses are arranged in two symmetric rows, which resembles both the shape and the general spatial distribution observed in real world. Modeled blocks are aggregations of houses configuring spatial grids composed by cells that are representing actual houses having particular states; these states in cells are assigned randomly at the setup of the model. Initial heterogeneous state conditions have effect on the potential of a given block to reach development. Another parameters are the block dimension or the number of cells composing the block, and the number of neighbors that are considered influencing upgrade. There is no absolute concept of time periods like months or years as the model runs over time steps; thus the number of time steps required to get block consolidation depends on the three above-mentioned parameters: number of seed or initial developed houses, block size and number of neighbors interacting and being influenced at a given time.

First model is a cellular automata (CA) model that runs through an updating rule, which creates or recreates a continuously changing spatial pattern into the clearly delimited block boundaries. Cellular automata produces ordered patterns and it is useful to measure this organization (Phipps and Langlois 1997). Validation of the model should replicate the initial composition and configuration (structure and function) in each studied block, the resulting outcomes are examined as path dependent through the random process defined explicitly by transition rule. This CA model is asynchronous, therefore target cells are selected randomly. Changes in cell states at each time step alter neighborhood configuration in the block, creating new spatial conditions at the new time step; therefore, conditions influencing state transition are changing. Updating rule is deterministic as the conditional logic operators define it, however important stochastic components are included first to select which of the operative cells are going to be evaluated.

A second model, addresses explicitly the social dimension in the process of consolidation by including a social network and replicating state transition through a model of epidemic diffusion. Social network is created into an Agent-based model (ABM) environment; households are linked conforming a social structure where they are grouped into three different groups according to their actual status at 2002: already upgraded state, not-upgraded yet, and delaying upgrade. Households interact and in principle could get influenced by already upgraded households; influence have effect according to an adapted diffusion mechanism. Probability to upgrade and delaying factor resembles the availability of resources (given the assumption that every household want to upgrade its house state if possible); these factors are taken from empirical data and therefore used in the initial settings.

Further description of the models and simulation is going to be presented using ODD (Overview, design concepts, and details) protocol (Grimm et al. 2010) and ODD+D (Overview, Design Concepts and Details) protocol (Muller et al. 2013). These methodological arrangements provide a logical description that makes the models to be both understandable and replicable.

6.3.1 Replication protocol CA

As it has been mentioned parametrization refers to such characteristics of the system that influences upgrading, and plays an important role in how the development rule drives agent performance. The rule is simple: detect and follow those houses in better condition, complexity arises as rules are applied into a heterogeneous environment and thus the key point is to track the different settings and its influences and identify those spatial configurations of house state that make both individual houses and entire block to develop faster. The general operation of the modeled system at block scale resembles that observed in house consolidation at block scale that is first characterized as a long term process where individual houses are upgrading independently its construction state (Tokeshi et al. 2005, Barros 2012). Along consolidation public utilities are credited not having influence in development. Progression of development by following the trajectory of spatial configuration of states in the houses into fixed block boundaries can be replicated by the operation of rules and also can be tracked along time steps. In order to implement the rules a formal algorithm should be envisaged (Figure 30), it addresses the mechanism of state-based interrelations and provokes spatial order to emerge from individual interactions. Used parameters are those identified in the context of informal development in Chillon valley; the only rule related to regulation is that that determines the maximum number of houses in each block.

This model is formalized through a protocol that is based on ODD (Overview, design concepts, and details) template protocol proposed by Grimm et al. (2010).

Purpose The purpose of the model is to simulate the consolidation process of houses into a block and to study how initial state composition and relative accessibility have effects on state transition process. The model intends to explain the foundation of the spatial pattern and state transition at block scale, in terms of both internal and external factors (local interaction and access respectively).

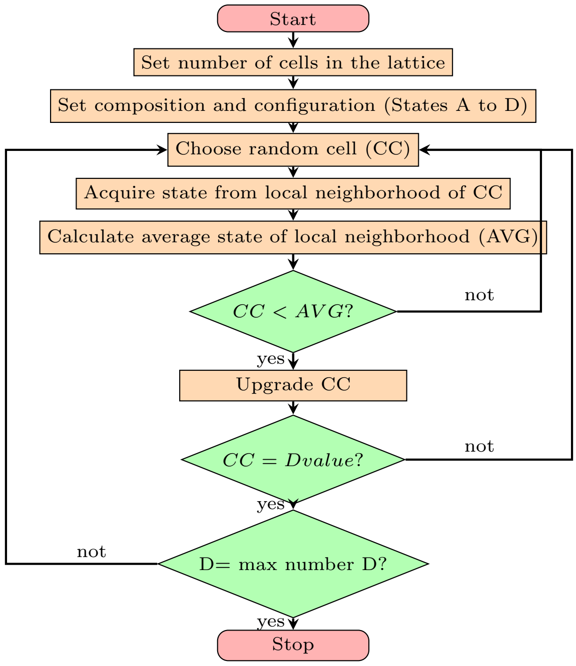


Figure 43: Algorithm for Cellular Automata model

Entities, state variables, and scales Main entities in the model are the houses, which are changing states from least developed state towards finished or consolidated houses. Agents are non mobile cells; these cells are organized into a clearly defined space: the block. Two initial parameters that define the model are block size and initial composition of state values into the block. The environment entity is the block, which groups the houses. House neighbors have effect on its state. The state variable is the construction state at any point of time for each house.

Process overview and scheduling The model is developed in Netlogo (Wilensky 1999). Time is discrete. Houses represented by not mobile cells, evaluate its state one per each time step using a simple updating rule that considers the average value of states in surrounding cells prior upgrading. Spatial relationships and effects among the cells are represented. Rule assumes a sensing property where "agents" read the state attribute of surrounding fellows. Reading means detecting state values in their neighborhood.

Initialization and calibration The space of the block form the environment in which houses interact and are influenced. The spatial configuration of the block comprises houses arranged in two rows of houses, which is typical in the observed housing blocks in Chillon valley. It is assumed that houses can read state information of surrounding houses; houses are the unique entities that contain this sensed information. Initial settings consider defining block size (the number of houses in the block) and the initial composition and configuration of states in the block. "The use of hierarchies is another way to calibrate a model; often the sequence of urbanization adheres to a particular formal sequence" (Torrens 2011); a important feature of the model is that a clear transition hierarchy exist in the real world; the sequence follow the consolidation unidirectional progress across states from A to D. Two additional and interchangeable conditional transition rules are also considered as stopping rule to cease state transition; they are the maximum number of houses on D state and the max number of time-steps; stopping rules are applied during initial settings and are based on values from empirical data. Calibration was performed by running the model 100 times to test the combined effect of the two access related conditional rules; results of the experiment show the effect on changing trajectories on the treated runs; slow transition effect is observed in the trajectories of A, B, and C states, while D state shows an early increasing of transition.

Sub-models Change of state in each house is determined by an updating rule that considers the relative influence of its neighbors; therefore if the average state value is equal or higher than that of the selected house, state is upgraded, if not it maintains its current value. The model only simulates state transition in residential houses, no other uses are considered. As houses are randomly selected for evaluation, they encounter different surrounding conditions that influence the decision to upgrade; thus the trajectory of state composition differs in each run, while maintaining constant the same initial parameters.

Treatment factors and experiment design Treatment factors are the parameters used to initialize the simulation; in this case they are: block size, state composition, spatial configuration, and access. The values of the parameters follow those identified in the study area. Table 6 summarizes the initial settings treatment factors and experiment design.

6.3.2 Replication protocol ABM

To make it possible replication of the model and simulation we describe the model using a formal protocol called ODD+D (Overview, Design Concepts and Details) that includes human decision-making (Muller et al. 2013).

Purpose The purpose is to simulate the transition in the construction state of a house that is as a function of interactions into the social structure composed by the households located into the boundaries of the housing block. Social structure is replicated as a social network where the influence of houses in a greater state is transmitted using a epidemic diffusion mechanism.

State variables and scales House construction state is the single state variable for the agents, these are the households who acquire their socio-economic status from the state of their houses; therefore state is used as a proxy of its socio-economic status in the process of consolidation. Construction state is categorized in to four types based

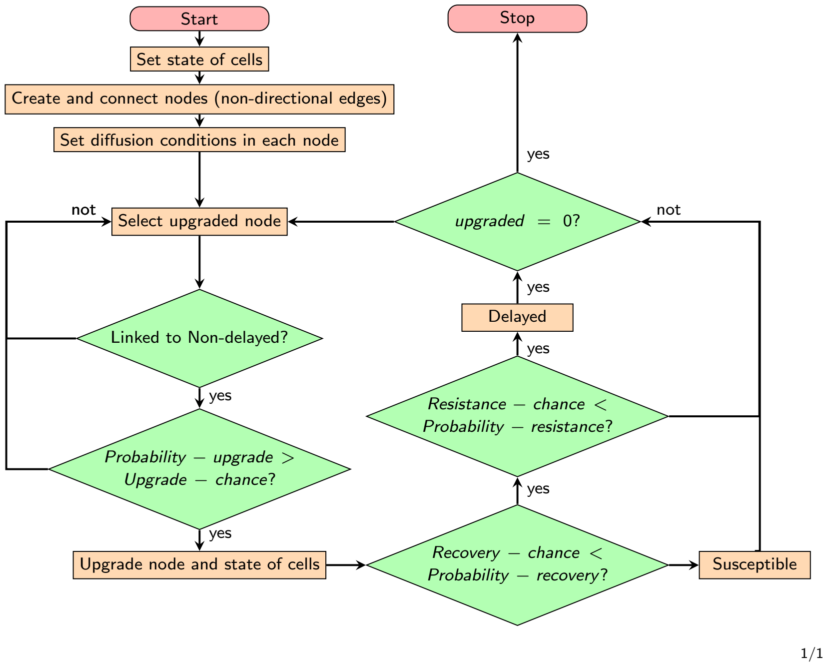


Figure 44: Algorithm of house upgrade diffusion

on observations at house scale along the process in Lima, performed by Tokeshi et al. (2005). Agents are linked to others into the space of the block by non-directed edges; links are allocated randomly and represents the stochastic distribution of groups of influence (small worlds) existing in the neighborhood located into the space of the block. Number of connected neighbors is fixed to three.

Process overview and schedule Hypothesized Influence operates through a model of epidemics diffusion called SIRS (Susceptible-Infected-Resistant-Susceptible). Analogous to first three states for the case of consolidation are the following agent states: Susceptible, Upgraded and Delayed. Diffusion algorithm operates into the initial settings of the network through discrete time steps. Nodes correspond to the households and non-directed edges are used to represent their relations into the network, which is assumed to have a random structure. Susceptible agents respond immediately to the influence of connected upgraded neighbors; once upgraded these agents become Delayed and still connected with initial associates can react to influences but its upgrade decision is related to an arbitrary probability that represents the level of affordability or resources availability to upgrade, which is an actual cause of delay in the process of upgrade the state. Therefore due to the mentioned two stochastic features of link selection and affordance the process have neither synchronization or repeated outputs; this leads to emergence of non-determinist state patterns and transition trajectories in the block.

Table 12: Initial settings for CA simulation in six selected blocks.

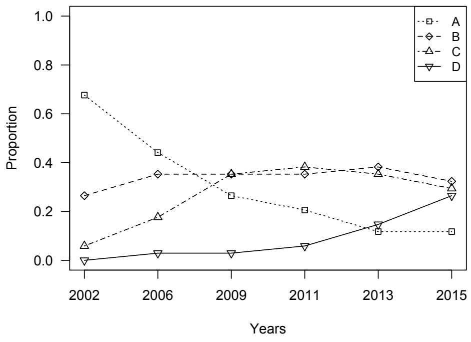
Parameter	1a	1c	2a	2b	6a	6c
Block size	34	24	24	28	35	27
Initial A	23	23	21	21	33	33
Initial B	9	9	2	2	2	2
Initial C	2	2	1	1	0	0
Repetitions	3	3	3	3	3	3
Final D (*)	9	5	2	8	1	7

(*) Stop condition

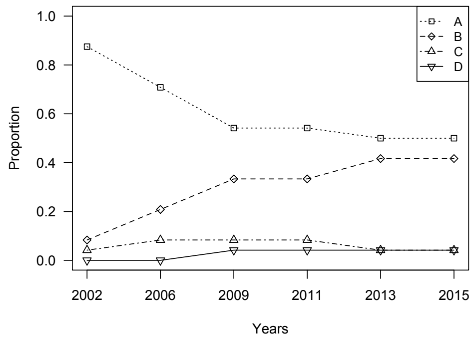
Theoretic and empirical background Computational model is composed by diffusion algorithm, lattice space, network structure (households and their relations) and initial parameters chosen from actual data; this system replicates consolidation process. As Roy et al. (2014) recommends the design of the model considers the spatial resolution of the data available (house state). Diffusion algorithm is based on SIRS model of epidemic diffusion, which reproduces the network of social contacts existent in the block; therefore house upgrade spread as a consequence of the influence from households having better house conditions. Model space is represented by a lattice of cells that have state attributes and are directly associated to the nodes (households) of the social network, thus conditions in the nodes have an effect on the state of the cell. The aforementioned social network is composed by nodes and edges; these elements are set at the beginning; node status considers the initial state values of the cells, and links are chosen randomly connecting edges between nodes; the number of edges are selected arbitrarily.

Individual decision making The subjects of decision are the households (a socio-economic entity) that set its status from the state of the houses (as objects). Upgrade decision-making effects are seen both spatially and temporally at the aggregated block scale. Households pursue to upgrade is conditioned by the resources affordance, which is replicated as the probabilities to either upgrade or delay it. The whole described decision rule that operates on each household is centralized and aggregated at network level, thus the diffusion rule constitutes the governing framework for simulating individual decisions. Households links are constant and therefore they adapt only to the changing conditions of their sub-group in the block. This sub-level of neighbors organization also relates the socio-economic influence network to the structure of block space.

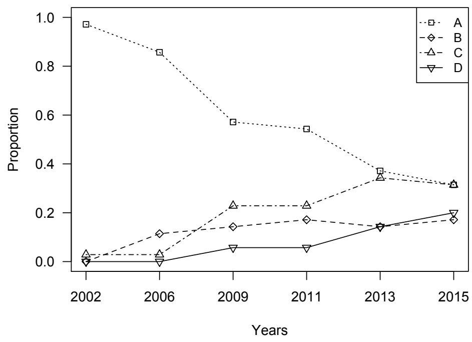
Interaction Direct interactions resulting from membership to the space of the block are assumed. Interactions are mediated by influence of household that have upgraded house state and the affordability to upgrade in influenced households. Upgrading takes effect if the household is influenceable. This interactions occur on networks defined by the spatial distances existent in the block neighborhood. The structure of random network is selected arbitrarily as actual links between households is unknown and the hypothesis that relations go beyond adjacency in local neighbors.



(a) Block 1a



(b) Block 2a



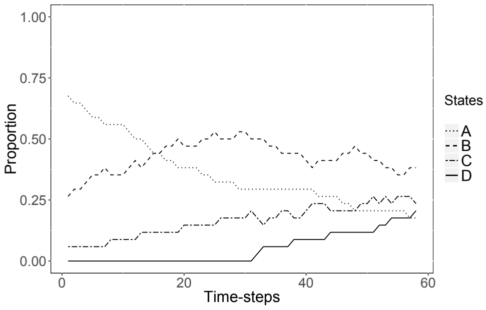
(c) Block 6a

Figure 45: Actual trajectories of state transition in informal houses

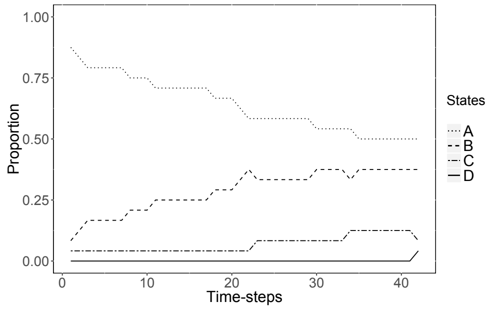
6.4 Simulation outcomes

6.4.1 Cellular Automata Simulation

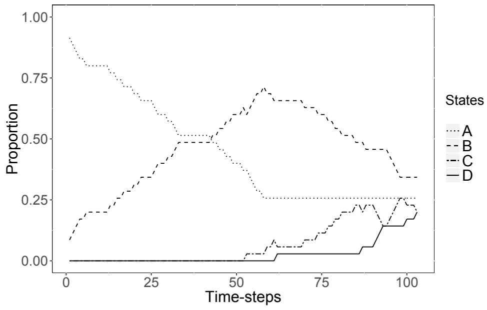
Initial settings It is worth noticeable that input used in the setup of the simulation comes from real world data, thus "agent properties are initialized using empirical data" (Zhang and Vorobeychik 2016). State composition and configuration in year 2002 is used in each of six selected blocks to initialize the simulation; therefore, simulation progress from initial conditions, through the intermediate steps and up to the end in 2015, is going to be comparable to actual trajectory of state transition in the period 2002 to 2015. Rule-based behavior in CA model is chosen to represent individual performance of house-related agents; dynamic interactions arises when rule is repeated along time steps; implementation of the rule modifies also the spatial configuration of house states into the lattice of blocks. Once initial settings are defined, algorithm selects randomly one of the A class cells into the lattice in order to start the rule operation; only one cell is selected



(a) Block 1a



(b) Block 2a

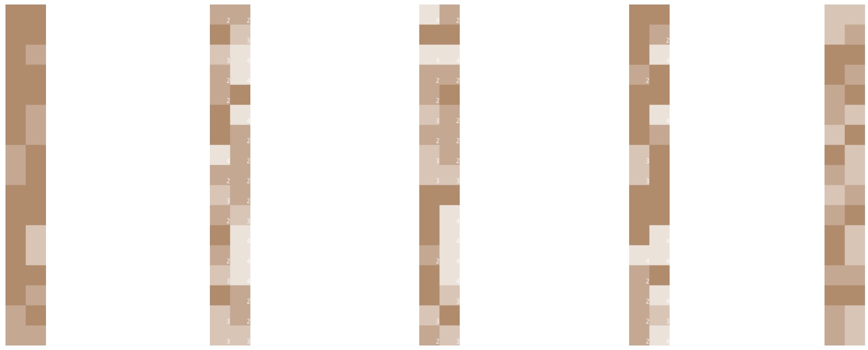


(c) Block 6a

Figure 46: CA simulated trajectories of state transition in informal houses

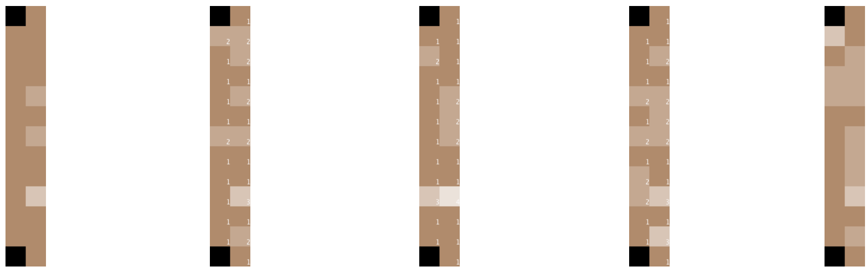
and evaluated against the rule at each time step. Rule is performed by observing the states in the selected neighbors; here is where rule is applied: if average state of neighbors is greater than that of the cell, then cell upgrades to the next state, if not another cell is selected randomly and as a result rule is performed on it. Along studied period state transition trajectories show a pattern of composition that resembles those observed in the blocks between 2002 and 2015 (Figures 36 and 37). Actual process is represented by maps and state transition graphics, simulated outcomes are presented similarly. The simulated process show houses in the block upgrading from initial construction states following the average state of surrounding houses until one of the houses reach the final state of construction. Different blocks are in different stages of evolution along consolidation; larger blocks appear to have larger periods to reach consolidation; thus there is a direct relationship between block size and time-steps. Consequently the model formalizes this fact by including a conditional rule for stopping the simulation; it is fixed in the maximum number of houses in state D at 2015; all the values and configuration in the initial settings, treatment factors, and experiment design are based on empirical data.

CA simulation outputs Model was run three times for each block condition, simulation ends when number of houses in D state reach the same number observed in year 2015. Results are presented in two formats: lattice configuration that represent idealized



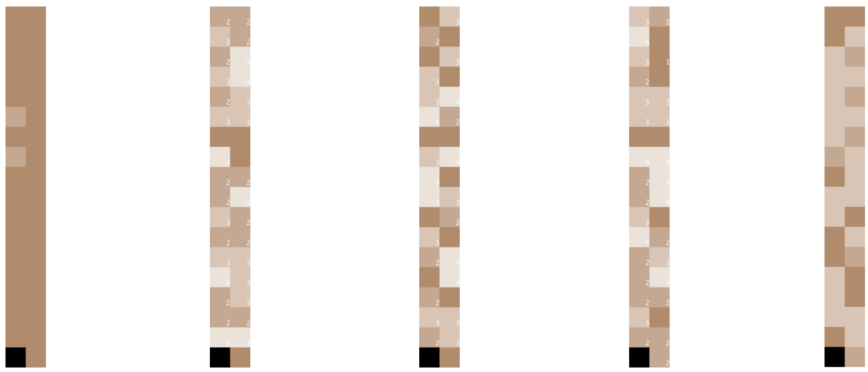
(a) Initial (b) Run 1 (c) Run 2 (d) Run 3 (e) Actual 2015

Figure 47: Lattice views of inputs and outputs configurations in block 1a



(a) Initial (b) Run 1 (c) Run 2 (d) Run 3 (e) Actual 2015

Figure 48: Lattice views of inputs and outputs configurations in block 2a



(a) Initial (b) Run 1 (c) Run 2 (d) Run 3 (e) Actual 2015

Figure 49: Lattice views of inputs and outputs configurations in block 6a

space in the block (Figure 40), and state transition trajectories (Figure 37), which is a time-series representation of the change in the number of houses in each state as this condition changes across time. Time steps is the relative time unit of simulation; these unit is approximately comparable to a single mont in absolute terms.

Table 13: Initial setting for ABM simulation in six selected blocks.

Parameter	1a	1c	2a	2b	6a	6c
Block size	34	24	24	28	35	27
Initial A	23	23	21	21	33	33
Initial B	9	9	2	2	2	2
Initial C	2	2	1	1	0	0
Number of neighbors	3	3	3	3	3	3
Upgrade-spread-chance	49	49	49	49	49	49
Recovery-chance	24	24	24	24	24	24
Gain-resistance-chance	35	35	35	35	35	35
Final D (*)	9	5	2	8	1	7

(*) Stop condition

6.4.2 ABM simulation

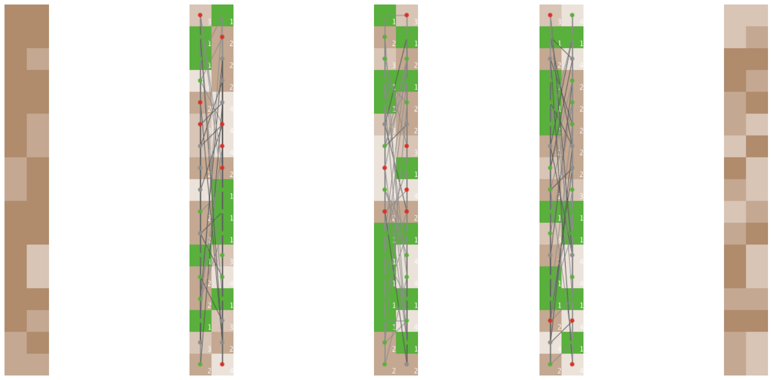
Initial settings Socio-spatial model is elaborated considering two aspects of informal urbanization and self-building process: the actual configuration at year 2002, and the diffusion parameters that regulates interactions between households and the decision to upgrade (Table 11). Initial parameters of diffusion are: Number of neighbors; the Upgrade-spread-chance, which is a transition probability calculated from data on observed transitions; the Recovery-chance that is the proportion of transitions in the period 2002-2009 that also repeated in the period 2009-2015; and the Gain-resistance-chance, which corresponds to the proportion of houses that changed in the first period but didn't in the second. To obtain the value of parameters for initialization, this research uses transition maps (Figure 20), which provides quantification on the probability of considered three possible conditions for upgrade diffusion: Upgrade-spread-chance, Recovery-chance, and Gain-resistance-chance.

ABM simulation outputs Spatial, temporal, and social configurations emerge from simulated interactions between independent households in the neighborhood (Figures 42, 43 and 44). Simulation outcomes reveal that few number of influencing neighbors are enough to generate the spatial and temporal configurations observed in real world. Two emergent phenomena arises in both spatial and temporal dimensions. In the former an heterogeneous pattern of states appear in the space of the block. Simulation outcomes represents a variety of patterns that are evaluated against actual configuration; validation is performed using Variant-invariant method (Brown et al. 2005).

6.5 Validation results

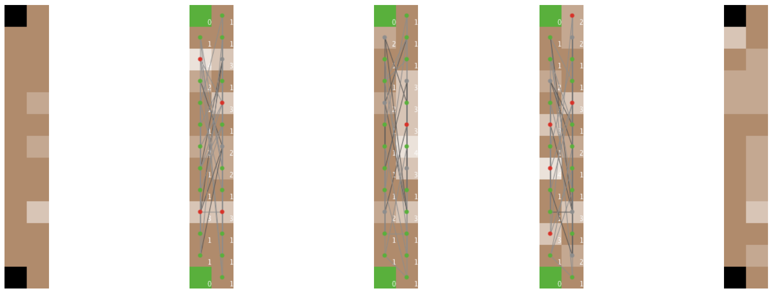
6.5.1 Validation of CA model

The CA consolidation model generates grouping and segregation between rich (C,D) and poor (A,B) classes; specifically agglomeration among initial higher states, which also are observed in the actual data, demonstrate the occurrence of path-dependence



(a) Initial (b) Run 1 (c) Run 2 (d) Run 3 (e) 2015

Figure 50: Lattice views of diffusion experiment for Block 1a

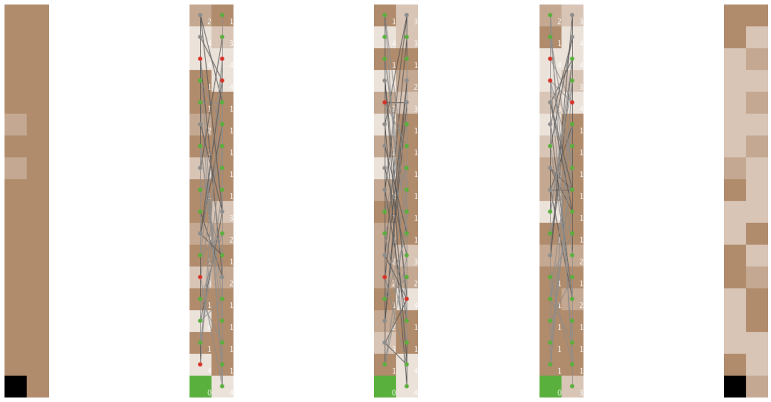


(a) Initial (b) Run 1 (c) Run 2 (d) Run 3 (e) 2015

Figure 51: Lattice views of diffusion experiment for Block 2a

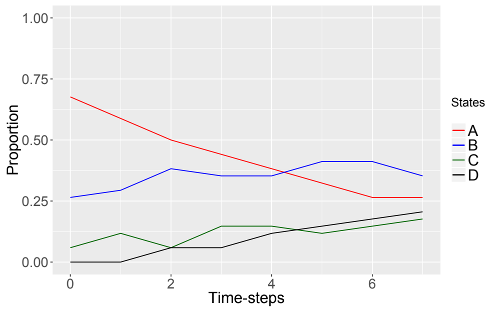
process. The Invariant-Variant method (Brown et al. 2005) help to identify and describe "how well the model performs, the situations or instances in which it does not perform well, and the cases in which it is relatively unlikely to predict well because of either path-dependence or stochastic uncertainty". Actual process is represented by maps and state transition graphics; simulated outcomes are presented similarly. House composition shows they are in different stages of evolution along consolidation; this variety in states drive emergence of heterogeneous spatial patterns at the scale of the block. The Invariant-Variant method is used to describe "how well the model performs, the situations or instances in which it does not perform well, and the cases in which it is relatively unlikely to predict well because of either path-dependence or stochastic uncertainty" (Brown et al. 2005). Initial four states are grouped in two categories or status: a) Consolidated (C and D) and b) Non-consolidated (A and B).

This method has the advantage to identify and measure the accuracy considering zones (cells) where allocation changes (variant) and does not change (invariant) across multiple runs of the model, giving a dynamic perspective on the performance of the model. Validation is applied in six representative residential blocks, whose size, and initial state composition and spatial configuration was reproduced by the model. Simu-

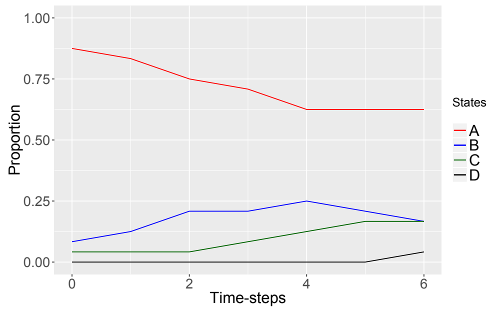


(a) Initial (b) Run 1 (c) Run 2 (d) Run 3 (e) 2015

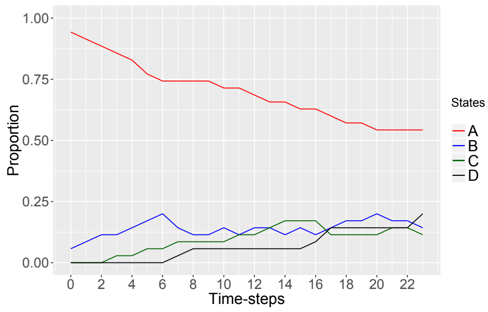
Figure 52: Lattice views of diffusion experiment for Block 6a



(a) Block 1a



(b) Block 2a



(c) Block 6a

Figure 53: Diffusion ABM simulated trajectories of state transition in informal houses

lation runs three times in each block and resulting spatial configuration was categorized per the above-mentioned two classes: Consolidated (R) and Non-consolidated (P). Average correct indicator compares spatial matching of simulated cells with those patterns retrieved from empirical data for the year 2015. Validation method employs the ratio C/R as an indicator of accuracy; this ratio is calculated by comparison of the number

Table 14: Validation indicators of CA model (Block 1a).

Indicator	Run R1	R2	R3
Average % Developed Correct	42	47	42
Invariant Developed (ID)	5	5	5
Invariant Under-developed (IU)	12	12	12
C/R	1,20	1.56	3.36
VC/VRD	0.51	0.84	3.19

Table 15: Validation indicators of CA model (Block 1c).

Indicator	Run R1	R2	R3
Average % Developed Correct	30	70	40
Invariant Developed (ID)	1	1	1
Invariant Under-developed (IU)	2	2	2
C/R	2.00	0.75	1.18
VC/VRD	1.68	0.64	0.98

Table 16: Validation indicators of CA model (Block 2a).

Indicator	Run R1	R2	R3
Average % Developed Correct	50	50	50
Invariant Developed (ID)	1	1	1
Invariant Under-developed (IU)	21	21	21
C/R	23.98	6.00	6.00
VC/VRD	0	0	0

Table 17: Validation indicators of CA model (Block 2b).

Indicator	Run R1	R2	R3
Average % Developed Correct	44	22	22
Invariant Developed (ID)	1	1	1
Invariant Under-developed (IU)	5	5	5
C/R	1.12	1.14	2.25
VC/VRD	0.82	0.61	1.36

of correct house status and position allocated by the model (C), against allocation by random selection (R). Accuracy in the whole model is based on the spatial outcomes where the invariant region of consolidated (ID) and non-consolidated status (IU) are considered, which is measured across multiple runs in the invariant zone that is always occupied by those houses that have either been correctly (IC) or incorrectly (II) allocated by the model. Accuracy considering only the variant region is implemented by comparing correct allocations in variable region to those allocations produced randomly, using the ratio VD/VRD.

Validation is performed calculating the values for CA outputs in each block (Tables

Table 18: Validation indicators of CA model (Block 6a).

Indicator	Run R1	R2	R3
Average % Developed	50	53	56
Correct Invariant Developed (ID)	6	6	6
Invariant Under-developed (IU)	7	7	7
C/R	1.09	1.09	1.23
VC/VRD	0.94	0.93	1.09

Table 19: Validation indicators of CA model (Block 6c).

Indicator	Run R1	R2	R3
Average % Developed	90	60	50
Correct Invariant Developed (ID)	6	6	6
Invariant Under-developed (IU)	1	1	1
C/R	0.95	0.83	0.53
VC/VRD	0.92	0.58	0.31

12, 13, 14, 15, 16, and 17); it is noticeable the effect of random allocation component in the updating rule along the simulated process of consolidation, given by the presence of a zone where different runs did not coincide (variant zones) and allocation of developed cells was not entirely determined by aggregation of similar categories. Values of C/R indicator in most blocks except 6c are greater than one, which means that accuracy is greater than 50% and therefore the model reproduces location of consolidated houses better than simple random allocation. Model performs well in invariant region and its spatial accuracy allows it to be generalizable for prediction of consolidation. In the other hand, most values of VC/VRD shows that in the variant region allocation is more due to random effect, and thus the rule is not representing well the process in the variant region. Specifically, these low values in the variant accuracy may describe that the model have the tendency of replicate different ways of consolidation in blocks 1a, 1c, 2b, 6a and 6b (block 2a has null values in this specific indicator). This indicator on the accuracy of the variant zone complement previous indicator; accuracy in the variant region show many blocks with low values compared with those from random allocation. Good C/R values indicates that the accuracy of the model relies mostly on matching the same invariant region many times and most of them correctly. Thus, using the status composition and configuration at the block, model have predictive accuracy, but does not show process accuracy as matches in the variant region are less predictive than random allocation, therefore in this variant region path dependence is based on random consolidation rather than a specific spatial influence by neighbors. Interpreted results show first that model predictability is limited when allocating non-consolidated blocks in most of the simulated cases. Moreover, as the selected blocks present a range of different initial conditions and sizes, these stochastic uncertainties in consolidation process (found in most blocks except block 6c), may indicate that this type of stochastic process is characteristic of house consolidation in the context of informal development. Block 6c

Table 20: Invariant-Variant Indicators of diffusion model (Block 1a).

	Run		
Indicator	R1	R2	R3
Average % Developed Correct	50	42	50
ID	3	3	3
IU	15	15	15
VC/VRD	0.58	0.67	0.89
C/R	1.21	1.40	1.69

Table 21: Invariant-Variant Indicators of diffusion model (Block 1c).

	Run		
Indicator	R1	R2	R3
Average % Developed Correct	30	30	60
ID	2	2	2
IU	10	10	10
VC/VRD	0.80	1.20	1.07
C/R	1.47	2.00	1.78

Table 22: Invariant-Variant Indicators of diffusion model (Block 2a).

	Run		
Indicator	R1	R2	R3
Average % Developed Correct	50	50	50
ID	2	2	2
IU	11	11	11
VC/VRD	0	0	0
C/R	0.96	0.67	0.96

Table 23: Invariant-Variant Indicators of diffusion model (Block 2b).

	Run		
Indicator	R1	R2	R3
Average % Developed Correct	11	0	33
ID	0	0	0
IU	16	16	16
VC/VRD	0.48	0	0.56
C/R	1.12	0	1.31

present both predictive and process accuracy and is an uncommon case among studied blocks. Thus, the model is generalizable as it contains an acceptable level of accuracy on the predictive capabilities in the other blocks; lack of accuracy in the variant region where the different run allocations show that path dependence is less dependent from the influence component of the updating rule than from its stochastic component of the rule.

6.5.2 Validation of ABM of diffusion

To perform validation, six blocks where selected from those that are present in the sampled sub-divided parcels. The primary condition of selection is that they have only present residential use, it is because the model is designed to represent specifically consolidation process in houses. Three simulation runs were performed on each block pa-

Table 24: Invariant-Variant Indicators of diffusion model (Block 6a).

	Run		
Indicator	R1	R2	R3
Average % Developed Correct	26	32	42
ID	2	2	2
IU	12	12	12
VC/VRD	0.93	0.95	1.34
C/R	1.45	1.46	1.95

Table 25: Invariant-Variant Indicators of diffusion model (Block 6c).

	Run		
Indicator	R1	R2	R3
Average % Developed Correct	30	40	40
ID	1	1	1
IU	4	4	4
VC/VRD	0.31	0.81	0.66
C/R	0.48	1.08	0.89

rameters; thus eighteen points were obtained from all the blocks for each of the two network models. Runs in each block generate outputs that are considered Independent and Identically Distributed (IID); thus runs in each block, which correspond to different initial conditions are analyzed independently. Accuracy indicator in network diffusion model does not present good values for any of six sampled blocks, but C/R perform well for all except for 6c. VC/VRD shows that in the variable region correct allocation of cells is due more to randomness, suggesting that uncertainty is a factor that is considered by the model.

Therefore, the model adopts both influence and stochastic factors of consolidation. Also, random influence suggested by VC/VRD values indicate that consolidation into the large variant region may not depend in neighbors' influence. It can be speculated that during initial stages of consolidation, existing conditions for upgrade relies more in individual housing needs than on influence from surrounded neighbors. By contrast C/R values indicates that houses are correctly allocated in the invariant region and performs better than if they are randomly allocated; matching in the invariant region further suggests that model is generalizable to replicate consolidation process and forecast state configuration of consolidated and not consolidated houses.

6.5.3 Influence across streets

A special case of simulation was developed in order to test influences across streets. A specific modification of Cellular Automata model is designed to simulate interactions between close neighbors across street. Local Von Newmann neighborhood is extended (to radius 2) in order to reach cells in neighbor block.

Results from simulation show temporal trajectories similar to those observed in real world; moreover, validation indicator C/R, show also that model generated configuration in the invariable region have higher accuracy than configuration from random allocation.

Outcomes show similar temporal patterns as observed in individual blocks, also val-

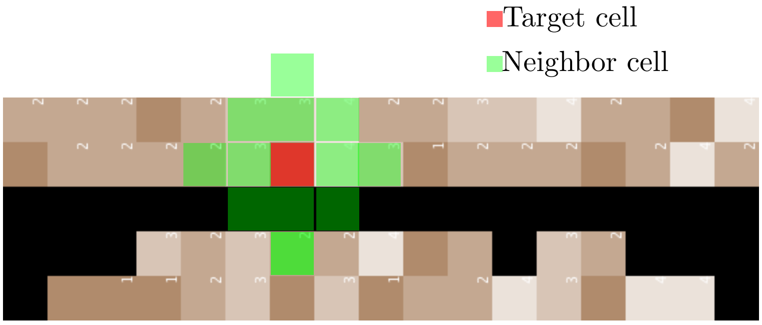


Figure 54: Von Newmann cell adjacency (radius = 2)

idation shows that accuracy is right enough to be considered representative of actual conditions. Two lessons can be learn from this experiment: first, in either single-block or extended block social interactions can be modeled as a spatial linkage represented by the local neighborhood of cells; and second, this analogy of interactions is working in different scales (1 and 2 blocks).

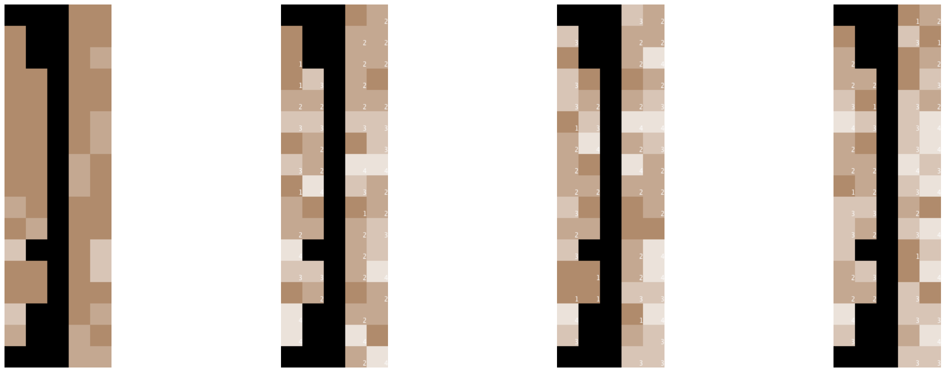
Table 26: Blocks 1a and 1b (radius=2).

	Run		
Indicator	R1	R2	R3
Average % Developed Correct	53	63	61
Invariant Developed (ID)	8	8	8
Invariant Underdeveloped (IU)	15	15	15
C/R	1.63	1.63	2.45
VC/VRD	1.17	1.17	2.34

6.6 Forecasting consolidation at block scale

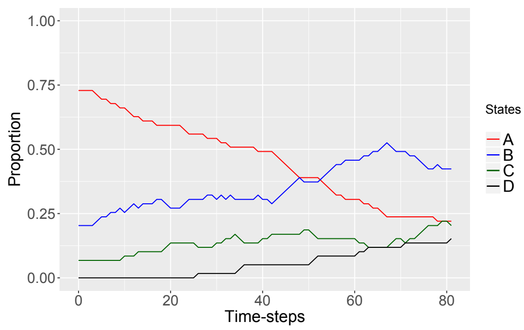
Model can estimate future from past values using time-series; using simulation block-scale settings are reproducing time-series properties on state variable that permits forecasting data under conditions of uncertainty observed in Consolidation (Figure 57). The focus is to employ temporal patterns of D state (Consolidated) because it is the information on this state that allows municipal managers to fulfill their requirements during land regularization activities.

Generated patterns (consolidation dynamics) match with the real time-series (2002-2015), proposed method of forecast uses a regression to model state composition trajec-

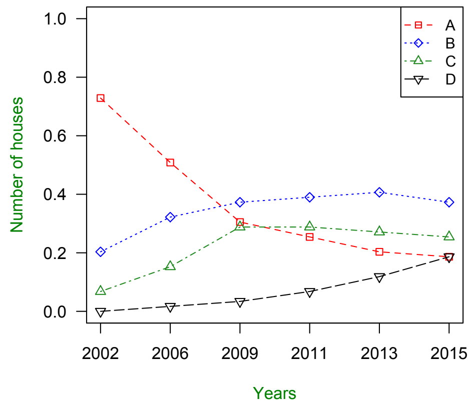


(a) Initial (b) Run 1 (c) Run 2 (d) Run 3

Figure 55: Spatial outcomes in the experiment across streets



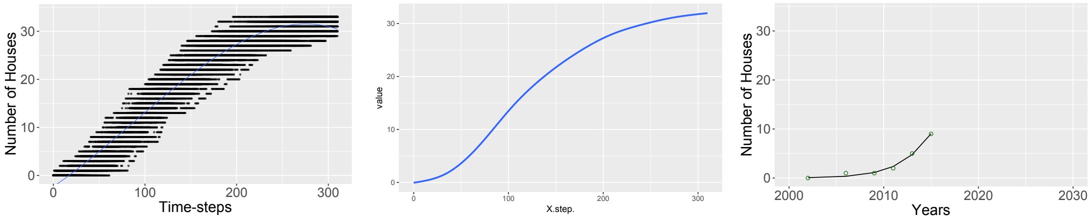
(a) Simulated blocks 1a and 1b (radius=2)



(b) Actual Block 1a

Figure 56: Trajectories of consolidation

tories of D class for a single block (Figure 58), which allows to estimate information in different settings at block scale, which allow estimation customization of regularization activities; this method also permits to get a relevant feature (tipping point) that could be used as a reference in the estimation of future conditions.



(a) Simulation points (b) Social network (c) Actual fit curve

Figure 57: Forecast tool development

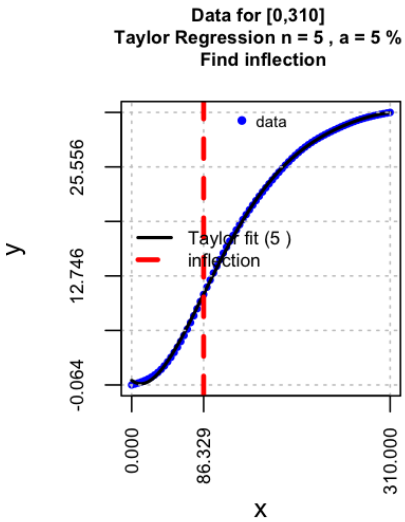


Figure 58: Sigmoid curve of D state (Block 1a)

7 Discussion

7.1 Interpretation and explanation of results

House state is the socio-economic indicator that is allowing to develop an exploratory and inductive analysis of consolidation process at micro-scale; in a first stage of this investigation, sampling is performed by identifying physically manifest structures that are used for progressive observation and identification of consolidation at parcel, block and house scales, according to a devised method of visual identification and classification. At bottom scale, these houses are the basic units of city structure, which are treated as independent development units with individual attributes of state and location within the block. House state is thus considered a proxy that make it possible to determine household status. Remotely-sensed imagery is used to extract construction features and classify the houses according to four classes; a devised visual identification protocol is allowing to make this step replicable. Resultant classification maps of house state distribution are therefore used to find spatial patterns that are employed to build the model and corresponding algorithm; the spatial data base is employed as a reference for model calibration and validation as well. Current analysis correspond to a longitudinal research that involves the houses as single subjects whose state is measured repeatedly each time-step over a defined period of consolidation that replicates the actual timeline from 2002 to 2015.

In the next stage spatial autocorrelation analysis is employed to measure and determine if construction state in a given house is spatially dependent on the state of neighboring houses. Physical and spatial data from housing structures present in the block are organized and analyzed through a statistical method called Join Count statistics (Cliff and Ord 1981) in order to characterize the actual process of consolidation across the actual period. Join Count statistics measure the number of joins or adjacencies between developed and non-developed areas; this analysis is performed at block scale evaluating if adjacency between developed or consolidated houses describe a particular pattern of relationship or is the result of a random allocation. Results showed no spatial dependence along the process; this empirical based finding suggest that a random allocation rule of states should be considered in the model. Statistics of the binary maps across the years, describe progress of densification or clustering in the actual map, which suggest that the Join Count statistics performed well describing tendency, even as it is clearly stochastic.

Following the investigation through the third stage two models are constructed; these models admit explicitly the spatial and temporal nature of different types of houses and its local relationships into the space of the block. Both consolidation models (cellular automata and social network diffusion) are designed to explore state transition process along space and time for the specific case of informal development at the scale of the house; these models uses fine spatial scale datasets as suggested by Samat (2006). Consolidation models represent the hypothesized factor that is credited to be driving the process: social influence. Operating algorithms incorporate the observed spatial-based random nature of house state transition. Models replicate the regular space of a informal block as a lattice; at this fine scale each cell correspond to a single house, and these houses are arranged in two symmetric rows, which resembles both the shape and the general spatial distribution observed in real world blocks.

It is assumed that the whole Consolidation system is observable at block scale by construction state features identified through satellite imagery, which can describe the system operation. In the block-house framework these accessible outputs can be referred to the spatial and structural attributes of the objects. These outputs depend on two main variables or parameters: time, and internal state of consolidation system.

Simulation of the model create random spatial configuration into the block space similar to those observed in the analyzed cases; although socio-spatial framework and state transition mechanism is different for each model, simulation rule is simple: detect and upgrade if adjacent or linked neighbor house has greater state than the evaluated house; resultant spatial and temporal pattern of state in the simulation appears quite similar to those trends observed in either actual spatial configuration or actual trajectories of state transition.

Validation depends on the objective of the model; in this sense accurate predictions are not the unique goal, rather the objective is "to reproduce critical systems properties in terms of spatial and temporal dynamics" (Barros 2012). Validation suggests that the models can reproduce dynamics of state transition and therefore, be useful for prediction. Applied validation method (Brown et al. 2005) have the advantage to identify and measure model accuracy considering zones that changes (variant) and does not change (invariant) across multiple runs of the model, giving a dynamic perspective on the performance of the model. Size and accuracy of invariant consolidated zone in the blocks is maintained almost constant across multiple runs; invariant number of cells are smaller compared to the number of cells reported in the variant zone; for this reason predominant variant results indicate that the simulation outcomes replicate the influence of particular stochastic events such as individual decision-making, that make consolidation path-dependent. Good accuracy within the invariant zone across the process confirms that the patterns of consolidation are clearly dependent on the location of early developed cells that continue development. It also shows the random effect of the rule along the simulated process of consolidation, because allocation of developed cells was not entirely determined by aggregation, leading to a large zone where different runs did not coincide (variant zones). The outcomes in every case show a very small invariant zone, which influences negatively the overall prediction accuracy.

Thus, the following research sequence has constitute the framework of performed experimental research:

- Data acquisition
- Spatial autocorrelation analysis
- Models protocol for replication
- Simulation outputs
- Validation

7.2 Answer to research questions

This study is dedicated to identify the sufficient and necessarily model elements and simulation outputs that better describe the whole dynamic operation of consolidation. Proposed method provide innovative and rigorous framework for analyzing state heterogeneity that plausibly generates tension between each housing unit and surrounded conditions; therefore, variety of states in house allow to infer the variables and parameters that make houses to be progressively developed. A working assumption is that the selected representation of internal structure as an socio-spatial set of agents make it easy to identify relevant outputs that are going to be used for the whole system description at block scale. Thus, the study estimates the internal state at every time step, by employing experimental outputs from both spatial analysis and agent based modeling. Empirically-based developed analogies of consolidation system at block scale includes housing space; resulting simulation outputs are accessible for validation and interpretation of spatial and physical attributes of houses and blocks and its dynamics.

The difference between temporal and spatial outcomes and real world are calculated using validation metrics from each CA and ABM models. Validation method evaluates the model output allocation, and two separated regions of cells within the grid are distinguished along the simulation according to its tendency to present change: variant or invariant. Accuracy values obtained in both models are enough to consider these general models replicable under the following conditions of informal development: self-help construction and regular block layout. Values of indicator C/R, in both models, points out that accuracy of the models relies mostly on matching the same invariant region of the block many times and most of them correctly. However, complementary accuracy indicator (VC/VRD) shows that in the variant region, allocation is more due to random effect. Therefore, it can be speculated that during the first moments of consolidation, models have the tendency to match correctly those cells that develop or not; moreover, these behavior exhibits path dependence because non changed cell locations corresponds to those houses that are relying on previous conditions to decide to develop. Thus, as not only influence is associated to state transition but in parallel own history (path dependence) is taken into account, models represent adequately the independent aspect of house upgrading suggested by Williams (2005): it is based on households' fulfillment of its individual housing needs.

The two conceptual models of social influence driving consolidation, are focused on represent the following chain of events that are stated by theories on social influence: interactions affects households and as a consequence households causes upgrade. Influence operates under the household autonomy; therefore, households as the actor and influence as the force, create and compose the dynamics of consolidation system. Observed location of houses that upgraded suggest that this attribute does not matter during consolidation, it has also be tested by Spatial Autocorrelation, and by the models whose simulation outcomes show similar accuracy without considering the type of neighbor location: adjacent or random. Therefore, it could be asserted that under the conditions of the experiment, perception within the block space is an important element of consolidation.

Based on the review of secondary sources of surveys at household state regarding consolidation in Lima, actors, driving forces and social interactions are detected to be present during consolidation process in informally developed houses in Lima. The research approximation through interactions and influence permit to extend the process out of a single house and relate it with other neighbor houses at block scale, allowing to have a broader spatial and social perspective of urban change, which itself permit to address current policy application. This bottom level approximation match the scale of consolidation with the policy intervention implemented by municipal managers.

The causal chain "neighbors' influence - household - upgrade" is very intuitive and subsequent efforts made in this research to explain this chain are valuable for analyzing consolidation system. Since house state and neighbors's influence are important components of the system data and information at this scale is also considered important and necessary. Data on house state is acquired from high-resolution imagery, whereas data and information on influence is derived from both existing surveys at household state and theories of social influence. To integrate the data it has been necessarily to design specifically for this case an appropriate combination of methods that allow successfully to bridge the gap on data availability at micro-scale; thus, scale has not limited to perform the analysis. Moreover, devised methodology allow to further extrapolate the house scale towards block and settlement, which have multiple benefits such as updating Census data and provide information on population or housing conditions.

7.3 On the selected approach

Top-down solutions (e.g. zoning regulations) does not address actual dynamic change produced at bottom level, as many plan revisions and house-level legal regularization of informally built houses show. Every time new municipal norms appear to regularize already done facts in informal urbanization, such as presence of houses in former agricultural parcels. Selected approach connect empirical data and theory within each of these simplified models of the complex system of house consolidation at the fundamental scale of individuals, in order to produce compressed and efficient explanations and descriptions of the real world using information theory framework.

The nature of house consolidation is identified at bottom level; at this scale interactions between households belonging the same block are considered plausible due to proximity. Theories of Social Influence (Festinger 1954, Degroot 1974, Axelrod 1997), provide the foundations to develop the hypothesis of influence driving house state transition in a neighborhood; moreover, Edmonds (2006) suggestion to employ space as a proxy for social relations has been followed in this research.

Therefore, house upgrading is hypothesized as dependent of the chance each house have to evaluate itself to surrounding neighbors; this is the main characteristic of the two applied rules: updating and diffusion. These rules permit to represent complex features observed in the actual process; the first is the subtle differentiation observed in the status of householders; two groups of householders appeared during classification: Rich and Poor; the first two were able to reach consolidation states C and D during the study period; the last group stagnated and comprises those that did not upgrade beyond state B. These two categories emerge during simulation; related outcomes refers to the number of houses and the spatial distribution of each household status at the end of the controlled in-silico experiments; block composition and configuration keeps very similar along the model runnings, and they present similar characteristics compared to real world patterns.

Results from the six simulated blocks indicates that the degree of predictability in the model was affected by the random allocation rule for evaluating upgrade, as it is showed in the poor accuracy values in the variable region of the block lattice, which corresponds to those cell locations that model choose to allocate variably across runs. Designed rules provide a generalizable method and include the stochastic allocation observed in the actual process, as spatial autocorrelation analysis show. Another factor affecting predictability itself (nor validity of the model) is the number of state categories accounted in the simulation outcome. Evaluation considering four-classes are considered not adequate when measuring model accuracy because of the unrealistically low chance that the general rules (the fundamental algorithms) have on matching the small number of spatial locations in the actual block lattice; therefore, overall accuracy and Kappa indicators will likely show very low values.

However, predictability raises greatly when outcomes are aggregated; two-classes results are fairly accurate and its analysis provides better indicators to analyze the process through path-dependence, this process leads to a emerging aggregation of status in locations that have an history of being upgraded or not in previous times. It is worth mentioning that the roots of this this aggregation are on the considered algorithms, which captures the influence between similar classes and shows very generalizable in the present study of consolidation dynamics at block scale.

Results confirm that is very difficult to predict the right spatial configuration consistently when there are multiple paths of consolidation possible (due to the stochastic component in the rule), even when the model is able to reproduce quite well the process of state transition and the aggregate spatial patterns, which is included in the influence effects. Therefore current consolidation models that are producing outcomes with an acceptable degree of accuracy and predictability under stated assumptions. Both models reproduce and predict the consolidation process acceptably; this capacity open the possibilities for future applications in urban planning, specifically in cases where data is unavailable, and thus on planning approaches that consider scenarios building or “what if” questions.

7.4 Critical evaluation of modeling approach

Informal housing structures of parcel, block and lot are identified and described in Chillon valley, and employed to replicate house state transition based on decisions that households make in response to influence signaled from their neighborhood. For the case of decision-making implementation “heuristic adoption models are often used when modelers are not aware of any established theory of agent decision making in the studied application” (Zhang and Vorobeychik 2016). This premise remarks a social aspect of consolidation process that guides this investigation in the direction of an empirically-based exploration of consolidation using computational tools, as an effort to contribute in building a theory of house consolidation at micro-scale that can explain observed dynamic patterns.

The process that produce improvement in house state and densification in blocks is replicated by treating them as socio-economic units; non-linear evolution of these changes in state through time is simulated and compared to real conditions. Models has proved to be generalizable to simulate consolidation in other locations in Chillon valley, and has potential to be applied in other Peruvian coastal valleys that share same self-help building procedure, housing typology, block layout, and whose parcels are located in the urban-rural fringe are under process of subdivision.

Conditions that drive house consolidation are credited to be social and spatial; thus, they are the result of interactions between households as construction of houses progresses, assuming that household is constantly monitoring neighbors house states and being influenced by those in higher states. These hypotheses were tested using two models and results show that both individual housing needs and social influence are driving state transition along time. As the period of study comprises early stages of consolidation, and observing that as consolidation progresses the number of "Rich" houses increases as well, one can speculate that there is a form of adaptive behavior in the modeled agents as the composition and configuration of block changes during stages of consolidation; households tend to follow their own history of past state transitions independently form others but keeping the pace of changing conditions in neighbors state. Households adapt their strategies of construction according to internal housing needs and external changing conditions of other houses inside the block; in doing so they not only consider their individual housing needs, but in parallel as consolidation progresses within block space, they may try to follow conditions in the block allocating an increasing amount of resources in order to afford upgrading. Thus, as new physical and social conditions appear new questions emerge from the study resulting from the outcomes of selected dynamic approach; these questions focus on new demographic and economic conditions appearing during consolidation; they require further investigation in order to provide insights in more practical realms such as cadastral update, tax collection, or municipal services allocation and timing.

7.5 On social influence to upgrade

Although spatial and physical factors are determinant in consolidation process, contextual social factor are credited to complement the process by giving the system its changing mechanism to make it possible its operation. Moreover, relationship between physical factor and consolidation is straightforward; however, relationship between consolidation and social factor is more subtle, it is complex. Review of field surveys at individual household scale in informal settlements located in Lima, provide insights on last relationship; it is suggested that interactions exists as community organization is a common practice in informal contexts (Williams 2005, Tokeshi et al. 2005, Peek 2014, Tamura 2014); also as individual households look for improve conditions, it is also acknowledged that there is contagion of house typologies (Tokeshi et al. 2005), confirming that households monitor its neighborhood conditions. Last paragraphs recognize implicitly that interactions not only serve group objectives, it also respond to individual evaluation that is reflected in decision to improve houses once it is affordable financially.

Thus, in order to model the social component of the system it must be determined if consolidation is caused by perceived physical conditions of surrounding neighbors. Confirmation of this hypothesized behavior of households address directly the question of how consolidation system operates and how spatial and temporal patterns emerges bottom-up from interactions. It is time now to include social influence within the discussion. As a concept Social Influence was defined by Moussaid et al. (2013) as "a change in an individual's actions that results from interaction with another individual or group". Social influence elements has been included within two devised models; the first CA model uses an simple updating rule where cells (houses) evaluate its state and upgrade it depending on average state of adjacent cells. ABM model uses a more sophisticated and explicit social structure within block space according to a suggestion made by Alam and Geller (2012) who stated that "modeling a social network requires identifying the spaces in which the agents exist and are related". ABM uses a random network where edges link nodes stochastic; this random network is a small world, this means that "most nodes are not neighbors of one another, but the neighbors of any given node are likely to be neighbors of each other and most nodes can be reached from every other node by a small number of hops or steps".

Both CA and ABM represent well the heterogeneous state composition prevalent in houses under consolidation, but they differ in the stress that physical dimension has in the former compared with social dimension in the later. Finally as results from validation show similar accuracy in simulation outcomes between these models, it could be interpreted that each dimension has equal importance on consolidation.

7.6 On forecasting state

Selected modeling approach uses interactions as a component that provides stochastic results to emerge, which is different from deterministic models that estimate directly and invariably the values (Figure 59). Application of research to forecast is based in the capacity of models to estimate future values in time-series given validated past values; forecasting data imply planning under conditions of uncertainty. Forecasting include various block-scale settings that are reproducing time-series properties on state variable. Different agents interacting among themselves are forming temporal patterns; generated patterns of consolidation match with the real time-series (2002-2015); outcomes refer to estimated values of state configuration in the block.

Quantifying patterns for state D allow model to be employed as a forecasting tool in urban planning recognize spatial and social components of consolidation system that are driving growth. Simulation outcomes provides data to perform regression; resultant regression model for trajectory of D state is aimed to obtain a turning point that permits estimate the time where the maximum rate of state transition occurs. It will be used for forecasting the amount of houses in D state.

Proposed method match conditions where there is not data available, or is very

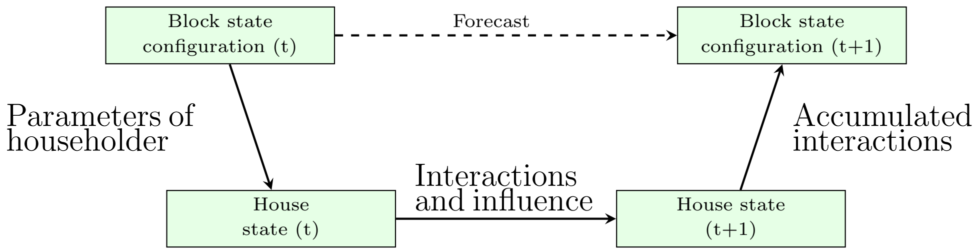


Figure 59: Forecasting scheme using time series: route through interactions

expensive to obtain; moreover it fits to planning methods that are used in such cases: scenario planning and “what if” explorations. A tipping point appears around 16% of total time-steps in the regression-based sigmoidal curve, where the number of D class cells starts a steadily increment and along with it a decrease in the number of both B and C class cells; it is also noticeable that this decreasing happens almost in parallel, making more certain the hypothesized shared nature of both states as transitional and thus closely related; this fact have a possible future effect for housing policy prescriptions in informal development contexts.

Application of the two developed models on local planning, and specifically on building future scenarios, are supported by the following facts obtained through research:

- Transparent data retrieve procedure, assumptions, model protocol, code, and validation are documented and freely accessible,
- resultant general model is used for cross-site comparison,
- model is balancing generality with the complexity of individual cases,
- outcomes have replicated consolidation sufficiently, and thus are producing meaningful results.

8 Conclusions

8.1 On research approach

This research addresses the problem of informal urbanization by focusing the study at the common and relevant process of house state transition along time, called house consolidation, which characterizes urban growth and densification in northern fringe of Lima metropolitan area. Mentioned phenomena is approached from complexity concepts that allows the handling of dynamic attribute of construction state in individual houses, which is heterogeneously distributed within block space. Assuming that household status is related to construction state, and that due to proximity, interactions are expected to happen in this social-prone neighborhood. Spatial processes and social interactions are related using explicit socio-spatial rules that replicate observed spatial configurations and state transition trajectories. Thus, house as structural elements and social-generated change breeds dynamics of consolidation as complex system, which is allowing to reproduce and interpret emergent spatial and temporal patterns.

This investigation is recognizing an important element of urban growth at the urban fringe, land subdivision within informal development context, which is produced as result of independent and decentralized decision by small agricultural landowners. Urban growth and both house and population densification produces urban fabric in a permanent change condition far from equilibrium, where increasing interactions produces economic value first reflected in houses values among other quantifiable benefits of urbanization.

The object of study is house consolidation, it is credited to be the result of individual pursue of households that decide to upgrade their houses based on housing needs and neighbors influence, which is implemented through self-help construction procedures. Using a simple spatial allocation scheme based on interactions modeled by either updating rule or diffusion into a network, spatial temporal trajectories of consolidation of houses are simulated in conditions that correspond to different levels of interaction under space constraints, reflecting different spatial composition and configuration of sampled blocks. Updating and diffusion rules drive consolidation of houses into space of blocks. A shortcoming of urban theory in explaining informal development at the scale of houses was detected in the literature review, including a lack of specific and explicit method to investigate specific phenomena of house consolidation using fine grained individual data. This research is a contribution to fulfill lack of methods and data, and therefore is aiming to characterize and anticipate complex urban evolution, like this unequivocal and always present consolidation process. “Detailed geographical information from many data sources enables a shift from a macro-static view to a micro-macro dynamical view that is necessary for management and planning policies in a non-linear world” (Pumain 2017). Identified and described non-linear long term process of consolidation configures a complex adaptive system, whose dynamics are characterized at block scale using complexity theory and social influence concepts that are grouped within a devised computational system that generate non-linear spatial and temporal patterns at block scale.

8.2 On data acquisition

This systematic study of house consolidation in the context of informal development, is registering and analyzing data on spatial composition and configuration of house states at block scale in the period between years 2002 and 2015. These spatial and temporal data are used to generate rules of transition, investigating how the latest states are related to early conditions, which refers to the concept of path dependence that is characteristic in complex systems. This study provides a method to characterize of informal housing development at block and house scales by employing four categories of house state (Tokeshi et al. 2005), which identify construction features that are retrieved from visual identification of high-resolution satellite imagery. It has been observed in the empirical data that once parcel space is subdivided into blocks, they are itself being converted into a uniform grid of vacant lots; immediately after land subdivision, house construction begins in randomly allocated lots creating a early landscape where the initial states of construction across houses composing the block are different. Whatever, the most important feature that comes from subdivision is the constitution of blocks as spatial housing entities with clear boundaries and configuration that resembles the formal uniform grid of residential blocks delineated under Peruvian Construction Code development parameters. Therefore, house spatial attributes or state variables can be assigned to an specific area, which correspond to each individual unit in the subdivided block. Consequently, houses constitute first the spatial finest grain housing units which have geographical and physical nature, and second, are the units credited to interact each other according to rules that takes into account its individual and particular construction state and spatial proximity; houses are the minimum object of study and therefore the basic elements of the system; moreover, this correspond to what Schwirian (1983) identifies as basic elements of a neighborhood: people, place, interaction system, shared identification, and public symbols.

Trajectories of state transition along time are drawn by plotting empirical trends retrieved from block scale maps during the period of study. These graphic of transition trajectories are employed to identify patterns of change in target houses in relation to surrounding neighbors. Empirical data sets are indeed employed to conceptualize the models in a realistic way using actual composition and configuration of house construction states in the period between 2002 and 2015. Models allow to investigate the role of social interactions in the house consolidation process under the hypothesis of influence that households with higher states have over their neighbors in the state transition process. Further analysis of retrieved configuration in the neighborhood at the bottom level is suggested to make it possible to infer and detect spatial patterns of change. This direct recognition of space as element of analysis provide the setting to explore urbanization towards planning and policy applications with focus at bottom level and specifically on the mechanism of state transition.

8.3 On spatial dependence

In a first approximation to characterize quantitatively observed patterns of consolidation, a spatial autocorrelation indicator called Join Count statistics (JCS) is measuring pattern and change in adjacencies among finished houses (1:1) for three numbers of connections (k): 7, 14, and 21. Join Count statistics show values that does confirm Null Hypothesis of No Spatial Dependence, therefore house consolidated house status does not depend on neighbors consolidated status. These values shows increasing trajectory across years towards clustering values that are not enough to reach statistical significance related to adjacency. A detailed observation in the values show heterogeneous pattern of development in blocks were spatial dependency is no existent. Therefore, observed house development trajectories at block scale shows random configuration at each stage, and a progression towards spatial aggregation; identified random allocation constitutes the spatial nature of observed housing blocks patterns, and remarks the utility of a spatial-oriented investigation; however, described analysis is static and does not permit infer or explore on the dynamics of the mechanism that is driving continuous change. Characterization of the spatial nature of housing development at block scale employing spatial autocorrelation analysis show that location of consolidated house status at a given point in time does not depend on neighbors consolidated status. However, identifying changes in JCS across years, a trend can be identified the same way that Jay Lee (2001) observed when analyzing urbanization patterns. This trend moves within the values of no statistical significance regarding spatial dependence but shows a clear pattern towards clustering and thus reaching dependence at a time when the block is going to get filled up with more houses in consolidation status. Results suggest individual trajectories of consolidation traduced in random allocation of consolidation houses captured either by these JCS and by the maps of transition.

No spatial dependence may be well represented and explained by including a social framework that complement spatial dimension. This analytic framework could be represented by a dynamic rule, where consolidated neighbors are influencing development of non-consolidated ones in random allocations, without synchronization in their decisions to upgrade, and thus deciding independently. Two devised models of consolidation have captured an important aspect of the process of consolidation: the progressive random spatial evolution across time and space. It is where empirical data analyzed using spatial dependance indicator shows its utility.

8.4 On modeling house consolidation

"Planning deals with large inaccessible systems, so it derives its result from a study of these systems in model form" (Chadwick 1974). Models are designed to deal with the following issues in order to build a clear investigation-oriented framework: a) the object of study is consolidation process, which is investigated considering an architecture of individual-based models on the hypothesis of social influence; b) model include spatial and social relationships at block scale c) simulation identifies complexity-based properties of consolidation such as path dependence, d) emergent outcomes generate quantifiable and dynamic patterns, product of individual and independent decisions. Two built models correspond and acknowledges what Couclelis (2001) called Descriptive Model; thus under this framework research objectives of representing the dynamics in housing block consolidation, and fitting it with observed house state transition patterns in space and time. Findings reveal that residential informal development and social influence are dependent upon a set of relevant conditions regarding initial composition and configuration of house states at the block. A socially rooted determinant of consolidation is determined by two features: households' internal individual pursue addressing housing needs and interaction, and external social influence from neighbors who act in concert to produce the dynamic spatial pattern found in the urban system at bottom scale. In a macro-scale study of informal development in Latin American cities, Barros (2012) found that "high income cells act as a catalyst for urban development"; current research also study the mentioned characteristic of influence from neighbors in higher state by devising a micro-scale mechanism that operationalize that hypothesis and produce emerging properties from the bottom up.

"A simple model can generate aggregate patterns that match those seen in empirical data; this by no means proves that our model is correct, but it does suggest that our model has captured some aspects of the process of development" (Rand et al. 2003). The proposed consolidation model accomplished to reproduce state transition and actual aggregate patterns observed in the blocks at the end of study period (year 2015); through the process it has been identified non-linear transition trajectories and path dependence of household decisions. One important aspect that has been captured belongs to the dynamic and complex nature of the studied process: path-dependence; its presence have theoretical meaning as it confirm the identification of house consolidation within the block behaving as complex adaptive system; it also have connotation on the application of this property in practical solutions based on generated and interpreted quantitative information. As far as the model could predict the number of consolidated houses at any time it is also possible to customize designs and plans for future densities and levels of consolidation that would guide decisions and timing on private and public investment in urban services that will boost the pace of infrastructure improvement in the local scale of neighborhood or small informal settlements characteristic of Chillon valley. In informal development contexts each household decides to upgrade independently; therefore blocks does not fill-up completely; houses are built progressively. As this process progresses block-specific spatial configuration emerges, which shows heterogeneous patterns that seem not to have organization. Complexity says it is self-organized, and thus the importance to understand its function at bottom scale. Two models (Simple updating rule and Diffusion algorithm) are adapted to make it possible its use as state transition mechanisms. Simulations show that transition trends resembling actual conditions in the empirical dataset, can be generated assuming diffusion of upgrade across neighbors within space of the block. Consolidation management in informally developed blocks must be based on objective and quantitative criteria, which focuses primarily on spatial properties and social interactions. Empirical data analysis is oriented towards building the model and providing insights and simulated data to represent actual process.

Boundaries of agricultural parcel have had influenced internal configuration of blocks; as a result, block layout is influencing the process of house allocation and development, specifically through the number of housing units present within the block. Individual and independent pursue is an important characteristic of progressive self-help building, which addresses changing housing needs within the household. This process generates heterogeneous and dynamic spatial configuration of house state derived from diverse and changing housing needs at bottom level of household interactions.

8.5 On simulation outcomes

Simulation outputs reveal that few number of influencing neighbors are enough to generate the spatial and temporal configurations observed in real world. Both types of social influence Spatial adjacency (passive influence) and Diffusion (active influence), are theoretically based descriptions of two features adapted to existing in proximity-based social groups, which replicates consolidation and therefore can be used as factors for planning and policy prognosis and prescriptions. Outcome data analysis and model validation also indicates that combination of spatial aspects with explicit social elements provide the accuracy that models require in replicating temporal and spatial patterns. Spatial and temporal dimensions of house consolidation from the bottom-up in the context of informal development at block scale are replicated and described sufficiently as a result of both adjacency and diffusion algorithms. Contribution of this research is on recognizing necessity of include and represent individuals attributes and the dynamic role they play in consolidation, while explicit addressing the spatial dimension at bottom level: block space. Combining social interactions and spatial processes along time in the models is also a necessary requirement for producing dynamic simulations of real world process as it matches either temporal trajectories of construction state transition and spatial configurations at block level. Moreover, comparing these inferred spatial and social features of house consolidation with actual policies helps to address in a dynamic fashion urban growth and densification at local scale, allowing to obtain insights and recommendations grounded in the dynamic nature of consolidation at micro-scale.

Initial focus is oriented to test the existence of an explicit and systematic relationship between spatial and social structure at parcel scale; this original aim is approached by investigating the characteristics of spatial clustering of houses into the block boundaries, inferring influences derived from distance or closeness of surrounding neighbors that may cause the target house to upgrade. Results indicate that such relationship exists as it is a necessary condition to replicate spatial and temporal patterns of consolidation. Dynamic equilibrium is also a particular characteristic of the operating system at block scale, thus agents do not stop interaction and they continue as their states are either developed or non-developed. Last characteristic can be regarded as an assumption of the active role of households along development process. Another important feature is that at initial stages agents occupying vacant lots have more chance to upgrade, thus at least at the beginning they are not allowed to speculate. Bottom-up approaches have been explained and discussed within the urban planning realm and under the theoretical framework of the theory of complexity; this investigation suggest that systematizing the actual process through an computational analogy and allowing it to generate data can provide useful information on the trajectories of change in urban areas at micro-scale. Model accuracy has open the possibilities for applications in urban planning, specifically in cases where data is unavailable; moreover, estimated information match to scale and needs of regularization activities for informally developed areas. Models may inform the building of future scenarios, which will be important tools for municipal managers at block and parcel scale, as they could implement their formalization activities under customized data representing the variable landscape of house consolidation at bottom level.

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